THE AMERICAN

JOURNAL OF PSYCHOLOGY

VOL. V | NOVEMBER, 1892. | NO. 2

ON THE DEVELOPMENT OF VOLUNTARY MOTOR ABILITY.

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PREFACE

On the Requirements of Work in Experimental Psychology.

I.

Work in Experimental Psychology must meet two requirements. It must be carried out according to the best attained methods of scientific research; and its results must contribute something to the knowledge of conscious life. The latter requirement is sometimes expanded to mean that the contribution must throw effective light upon general problems of Psychology and Philosophy; and sometimes it is expanded to mean that the contribution must be of some practical use.

II.

The Experimental Psychologist has no choice and no wish for choice against the requirement for exact method. It is true, indeed, and needs emphasis, that in the present state of Psychology a vast deal is to be hoped in certain fields from very simple methods, intelligently planned. More exactness than the subject requires is pedantry and waste. It is a fundamental error to suppose that the same exactness in experiment, and the same strictness in deduction, are possible or useful in all scientific work. It is a principle of wide application that degree of system in procedure should correspond to the degree of system in the material and situation

to be dealt with. To establish in a logging camp, the governmental machinery which is found essential at Washington, to keep debit and credit for a kitchen garden with the system of books used in the New York Clearing House, to enforce at a fox-drive the discipline of the German army, would be ludicrous violations of the principle. But a multitude of examples no less ludicrous appear in the history of science. Systematic methodology has, hitherto, almost wholly failed to recognize that science is subject to the law of evolution,—*exists* in all degrees of development. The constantly recurring delusion has been, that processes found fruitful in the more highly developed and exact fields of science, may profitably be applied to all phenomena whatever. As a matter of fact, the "inexact sciences" are only burdened by "scholastische Zahlenhaufen" (Münsterberg's apt word), which are more precise than significant, or by strict deductions, whose strictness can be only in words. We need a logic based upon the historical development of science to set forth the whole law in this matter. Meanwhile the individual investigator must be a law unto himself.

At the same time it must not be forgotten that Physiological Psychology is not so new as its name. It is historically a special outgrowth of older sciences. Its oldest classics are the work of men trained in Physiological research. The modern Psychologist, accordingly, fails to find in his specialty a paradise of windfalls. He acquires, instead, a practical realization of Comte's generalization that the more complex science presupposes and works by means of the other sciences. If there were any such thing as a perfectly trained Experimental Psychologist, he must have had thorough apprenticeship not only in the results, but also in the technique of Chemistry, Physics, Morphology, Physiology and Mathematics. Or since no one man can have all these knowledges and skills, the body of Psychologists must have them. The combined results of human ingenuity in every direction may and must be made to bear upon the elusive problems of conscious life. Such concentration of all available forces upon the problem in hand is the ideal of every Psychological research. To do this, at least in the measure attained by works of standard excellence in the same field, is a requirement not to be escaped.

III.

The demand for results of general significance requires consideration. Perhaps no one has ever been more urgently called upon to consider this demand than the Experimental Psychologist. For, perhaps no one has been more urgently

solicited from within and from without to "keep his feet upon the earth and yet to carry his head among the stars." He is called upon to be both scientist and philosopher in one. As a matter of practical attitude, at any rate, every Psychologist must give the demand for general results some kind of answer.

This demand seems to be eminently rational. For progressive organization seems to be a universal character of growth. All evolution, organic and inorganic, conscious and unconscious, individual and racial, appears to involve advance of the relatively isolated into more perfect unity. The main occupation of every living thing seems to be the transformation of a relatively chaotic environment into stuff of finer organization; and degree of organizing capacity seems to be one fair measure of a being's place in nature.

One who has arrived at this conclusion, with whatever arguments therefor, is rarely undecided in his judgment of the relative value of concrete and general scientific results. The concrete scientific result, standing in no obvious relation to any general law, is not, he may allow, without value; but its value diminishes the more concrete and isolated it is. In the presence of the greater generalizations of science, such unrationalized bits of knowledge seem to him trifling; in the presence of the insights of philosophy, they become practically insignificant. From men who have this view, the demand upon Experimental Psychology for general results is particularly imperative. "Do your experiments throw light upon the nature of the soul?" they ask. "Do your statistics determine a system of Psychology? Does your delicate machine enable you to establish, or disestablish, any general law of mind? If not, if you have nothing to show but an uncorrelated fragment of information about the conscious life of infusoria, or about the knee jerk, or about the time in which you can wag your finger, all this may be very exact, but it is almost impertinent to call it a contribution to Psychology and it is altogether folly to call it a contribution to Philosophy."

What answer can be made?

1. In the first place, it is submitted, subject to the facts of the History of Science and Philosophy, that reaction against established general theories toward concrete reinvestigation from the ground up, has justified itself as an essential part of the process of intellectual growth. "Jeder tüchtiger Denker ist zuerst Zweifler," says Herbart. One must have studied the lives of the most productive men of history very superficially indeed not to see that this is so,—that the resolute skepticism, negation and descent which, for example, Des

Cartes describes in himself, must prepare the way for the more obviously profitable creative work.

The same thing appears no less in social Psychology. Mr. William T. Harris has observed, as one of the mysterious phases of the History of Philosophy, that the "shallow thought of Nominalism should have triumphed for a long period over the deeper and truer thought" of St. Thomas Aquinas and the orthodox theology. He offers in explanation of this mystery the consideration that the "deeper and truer thought," although it "emancipates humanity at first, after a time imposes on the soul a sort of external authority and needs to be replaced by a newer freedom." . . . . . "It is wonderful," he says, "to see how the most negative phases, the skepticisms, the heretical doctrines, the most revolutionary phases in history . . . . are destructive only in their undeveloped state and when partially understood. By and by they are drawn within the great positive movement, and we see how useful they are become."

Suppose now the results of Psychological research were as fragmentary and unmeaning as the most ignorant critic believes or hopes, how should we account historically for the social movement which has produced them? How could men who sat at the feet of Kant, Hegel, Herbart, and other such masters, turn away to these husks?

Might we not make a beginning of answer with the foregoing explanation of spiritual revolt? Might we not say that the modern movement in Psychology constitutes a protest against the final sufficiency of the howsoever superior systems which the world already possessed? If this movement were wholly negative, heretical and destructive, might we not expect that it would "by and by be drawn within the great positive movement" toward a philosophy, through it more rational and emancipating than those it forsakes.

No such revolt is nihilistic. It is essentially an appeal from the schematized reason of the books to the finer reason of reality. It is an expression of that saving discontent which drives men always from the good toward the everlasting better. To regard such a movement as a descent is an altogether distorted view. If it be descent, it is the descent in search for solider foundations. If we dig down, it is that we may build the higher.

2. We have, however, a far more fundamental justification of concrete Psychological research when we view it as —what it is intended to be—a contribution to a long cooperative task. This way of looking at individual work is very familiar in Philosophy and Higher Anthropology. From many sources ancient and modern, scientific and phil-

osophic, from Aristotle, Leibnitz, Hegel, Darwin and Spencer, we have some more or less explicit statement of this view. Human life in this world is regarded as a development, to which every man's individual accomplishment is a more or less important contribution. Therewith, conscious activities and attainments—whether of child, savage, average civilized man, poet, saint or philosopher—are made to appear as stadia in the growth of mind. We have, accordingly, at bottom the view of *a race working together*, consciously and unconsciously, by force of circumstances, by instinct, or by intelligent purpose, through the long task of comprehending the world.

This view carries with it two direct implications. The first is that *no* sort of intellectual effort is quite without justification. The ideas of childhood and of the childhood of our race, the myths, cosmogonies, and grotesque theologies, as well as the scientist's fact and the philosopher's generalization—who shall say that any one of these has contributed nothing to the development of culture? To despise the study of the conscious life of a spider is unphilosophic. To despise the study of the conscious life of Plato is unscientific. To be dismayed at the world full of warring ideas as though they threatened the Sovereignty of Reason is unintelligence and lack of faith. These derisions and fears are no doubt natural—to minds of a certain development—but they disappear from every mature and reverent view of the world. The second implication of this view is that intellectual values are not equal. It is not a theory of indifferentism. On the contrary, growing out of this view, or in essential harmony with it, is a universally recognized standard for valuing intellectual work, namely, how much has the work contributed toward accomplishing the intellectual task of the race?

Now it is a singular fact that while a philosopher is much the more apt to recognize this view in theory, a scientist is much the more apt to realize it in practice. The philosopher is very much inclined to limit the application of the theory to his predecessors and contemporaries. The instinct of the philosopher is to complete by himself, in the general, the intellectual task of the race. Very often he believes he has done so. In his system, the long intellectval evolution has culminated.[1]

[1]For illustration of this tendency in the philosopher, one thinks perhaps most readily of Hegel, whose exposition of the History of Philosophy as a necessary evolution, wherein individual systems are necessary successive stadia, is not felt by him to be inconsistent with the claim that his own system is a culmination of the evolution, a finally valid general view of all reality.

A not less interesting illustration of the same tendency is to be found

Quite otherwise the scientist. The Experimental Psychologist, for example, may or may not have a Philosophy of History wherein every man's work, including his own, is regarded as a small contribution to a social task. He may not have the theory, but he does the thing. From inclination or from resolution he foregoes the making of a system, and tries to furnish some material for one. He is cheerfully willing to fix one point and drive a peg down there, whether any other peg is in sight or not. He makes no apology for his uncorrelated fact. He denies the right of the present to determine its final value. He leaves it for the justification which time shall show. He is willing, in short, to make one in a vast social endeavor instead of trying to complete the whole task by himself.

The foregoing is intended to be a defense of concrete Psychological research, even when the results throw no immediate light upon general theories of life and mind. It has been for the time conceded that the results in Experimental Psychology are all of this character. The concession was, however, only temporary. It is flat ignorance to suppose that the body of Psychologists are working without intelligent aims, somewhat, for example, as the earth-worms, which contribute to civilization without intending to do so. It is true, indeed, that there are men in this as in other fields of science who profess horror of generalizations. When the History of Science is written from the Psychological standpoint, the etiology and uses of this type will no doubt be made to appear. It may be that those often skilful and productive scientists, whose fear of generalizations amounts to a phobia, represent the extreme swing of the pendulum from the other extreme of reckless speculation. They perhaps exhibit, in the social scientific movement, in a large and obvious way, that period of skepticism, negation and blind groping which the individual thinker generally passes through on his way to a more obviously productive period.

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in that present day philosopher who is popularly supposed to be the special champion of empirical science and the special foe of dogmatic philosophy. Mr. Herbert Spencer presents a system of First Principles, of which it is affirmed:

1. That Mr. Spencer is the first in the course of evolution fully to realize them. 2. That they are strictly deducible from an ultimate principle, which permits empirical illustration, but which does not permit empirical proof. 3. That they hold good for the whole and for every part of every one of an infinite number of successive epochs of world-evolution and dissolution. How it can be so confidently foreknown that the Unknowable—in which all things, changes and laws have their being—contains no potential modification of Mr. Spencer's valuable generalization, is not known to the writer.

Such periods are probably necessary to the philosopher, and such men are useful, negatively and positively, in the development of science, even if they generally are as they have been aptly called, "die Handwerker der Wissenschaft."

The leaders in Psychological research are, however, not at all of this description. The ignorant derision and neglect which so often express the attitude of the immature mind toward philosophy, find no sympathy from any recognized master in modern Psychology. It is, on the contrary, a fact that the leaders in this movement are not only acknowledged masters in experimental science but thoroughly schooled in philosophic disciplines. Munk has expressed the ideal in speaking of Helmholtz: "*Bei der genauesten Ermittelung des Einzelnen, das Ganze nicht aus dem Auge zu verliern; bei der Erwägung des Allgemeinen immer wieder Kraft und Sicherheit am Besonderen zu erproben*" (1). It is an inestimable good fortune that this is so. For a social movement, howsoever much it may be beyond the precise control of any man, is nevertheless even as other force, largely directed by the men who best understand it.

Under such leadership, the rapidly growing company of Psychologists have learned to take no narrow view of their common task. That study of the development of the unconscious world whose results make up most of what goes under the name of modern science, Psychology will supplement by a study of the development of conscious life, from its darkest beginnings to its apotheosis in science, philosophy and religion. This work, it is profoundly believed, cannot be forestalled by general laws, however obtained and however true. We cannot dispense with organized mortality statistics, because we know that all men are mortal. The most ingenious philosophic reflection cannot anticipate the special phenomena of human activity and the special laws which they will reveal. There is no device for avoiding the task which the actual, finite and definable interactions between individuals and society make possible and imperative. "Die Höhe reizt uns, nicht die Stufen" Gœthe's Wilhelm Meister is told. But the *Stufen* are not to be escaped. It is, therefore, evident that this must be, in the broadest meaning, a co-operative task. Money from men of wealth, or from all the people through the state; the experience and manual skill attained in the mechanic arts; the instruments, devices and discoveries of the older sciences; the suggestions of Philosophy back to the earliest myths; the divinations of art and religion; men able to plan, and men willing to work; all the forces in co-operative civilization must come together for the making of the Science of Psychology.

IV.

The demand for practical results, which has every meaning that varying stages of culture give to the word practical, has already received an implicit answer. As the most profound philosophy is most cautious against premature philosophizing, so the highest practical sagacity is least inclined to force premature practical results. The most impractical requirement upon science is to limit it to a search for alleged practical results. Wise men do not demand loaves from corn in the blade. Science must be allowed to develop in freedom and bring forth fruit in its season. If what is true makes the best direction for what to do, we may be sure that every truth found will prove itself practical in more and better ways than anyone has thought of hoping for.

Here again, however, Psychologists are not working without aim. The most practical questions, the questions in which men generally are most intensely interested—the questions of health, education, government and religion, which are deepest in the conscious and unconscious life of the world,—these are the questions for which modern Psychology is gathering force. Sagacious men are saying that the next years are to be the Psychological Epoch. There are, at any rate, abundant signs that that intense public interest in science which is always interest in man, even when it is fixed apparently upon some law of Copernicus, Lyell or Darwin, will be challenged next by the results of Psychological research. And it is fair to hope that this will be a schooling no less beneficial than the former ones have been.

The Development of Voluntary Motor Ability.

I.

In studies which involve the development of will, it has usually been thought necessary to begin or at least to conclude with a theory of the source of the force appearing in voluntary motion. This appears not only in works avowedly metaphysical, but scarcely less in works avowedly anti-metaphysical. This is so evident even in strenuously agnostic writings, that metaphysicians may very well appeal thereto as a profound historico-psychological justification of their own occupation.

Concerning the relation between special investigation and metaphysical postulates, explicit or implicit, nothing will here be said. But it is at any rate undeniable that investigators whose *explicit* metaphysical postulates are contradictory, make contributions to a common fund of knowledge. That this is the case even in the study of the development of

will in the individual or in the History of Culture, is a historical fact. How this can be so may appear from the following:

It is evident from the phenomena of growth and it is generally agreed that the activities of a living organism are determined at any point in its history, partly by influences from its environment and partly by the subjective constitution of the organism at that point in its history.

This generalization leaves open the question whether any part of the "subjective contribution" is essentially innate and independent of the rest of nature, or whether all subjective energies have been taken in from the environment and stored up by the individual and its ancestors. Instead of a solution of this metaphysical[1] dilemma, we have in the generalization only the outlines of a scientific task. Whether the metaphysical problem be solved or not, and however it might be solved, the scientific task remains the same. It is the task upon which all students of the growth of living things are in some way engaged.[2]

The study of the development of will in the individual as well as what may be called the development of the "social will" in the History of Culture may be regarded—must be regarded as part of this task. We have, namely, the conditions of a vast experiment. We have on the one hand the world of forces by which the activity and growth of the will are modifiable; an infinite range of things from barometric pressure and cookery, to educational systems and the Spirit of the Times. On the other hand, we have the fact that even the simplest neural reaction is not a simple reflection of the stimulus applied; but that cerebrum, spinal cord, or nerve-muscle machine, each in some degree contributes—from whatever ultimate source—to determine the resulting reaction, and so exhibits something of its own constitution. Every action of animal or man, whether elicited by the "natural" events of life, or by the device of the experimenter, becomes accordingly a source of information about the existing constitution of the subject. It is obvious that we have in this way a general method for studying individual and social development. The same kind of experimentation which shows what

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[1]By metaphysical I mean to describe the knowledge men are held to possess of the absolute nature and source of things. I call this a metaphysical dilemma because its solution seems possible only from a knowledge of the absolute nature and source of the force appearing in the organism.

[2]Among Morphologists, one finds the same dilemma, in the form of a dispute whether or not the embryo has any innate "formative force." Meanwhile men of both views work productively side by side.

the spinal cord can do, shows how much more the cerebrum can do. The same general method of observation which shows the capacity of a child, can follow the enlarging capacity of the child to modify his environment and to shape his own course therein. From the observed reactions or results of reaction of men upon the world, it is possible to write that history of human emancipation, which we call the History of Culture. We have thus a standpoint which leaves open every question as to the absolute nature and source of the forces appearing in action and which, nevertheless, permits the study of the will through every stage of its development, from the events to which the subject contributes.

In gaining this scientific point of view for the study of will, we have at the same time gained a reason for the study of voluntary muscular motion. For to the Psychologist oı Sociologist, it can not be an insignificant fact that:

"L'infinie diversité des manifestations extérieures de l'activité cérébrale,............................l' hilarité de l'enfant à la vue d'un jouet, le sourire de Garibaldi persécuté pour avoir trop aimé son pays, le tressaillement de la jeune fille à la première pensée d'amour, l'énonciation verbale des lois de Newton ....toutes les manifestations extérieures de l'activité cérébrale se réduisent aux mouvements musculaires." (2)

But the bare fact that all, even the highest, immediate manifestations of the mind are muscular motions does not at once make apparent the deeper justification for the study of those motions in Psychology and the History of Culture. The fact alleged is denied by no one. But many would hold that the motions involved in signing the Emancipation Proclamation, and those which a child might make with the same pen are so different in every respect which concerns Psychology or the History of Culture that their undoubted points of likeness may be neglected as trivial. It is, therefore, necessary to recall the fact that the activities which make up what is called the higher life of humanity are not isolated, but have inescapable connections with the activities and achievements which are usually called lower. It is seen, for example, by discerning men that the development of art, science, philosophy, political institutions—of all that goes under the name of cultivated life, has been made possible, in a large degree, by "material civilization." The more extensively and the more intensively the History of Culture is studied, the more does this historical dependence appear. The progressive attainment of material wealth is necessarily accompanied, in a somewhat corresponding degree, (1) by an increased knowledge of the laws of nature, (2) by an increased amount of force at disposal and an increased skill in its

manipulation, and (3) in consequence, by an increased freedom from the control of the immediate environment.

That the *outer* conditions essential to the development of higher culture are furnished in this way is evident from all historical study, even if it were not generally realized in the personal experience of men devoted to any form of cultivated life. Any work requiring leisure must have the leisure provided by some form of stored work. It is practically impossible for art or science to flourish except by help of the stored work, which material civilization has provided. "Before we can live well, we must manage to live."

It is less evident but more, rather than less important that the *inner* conditions of higher culture are prepared by the struggle for material wealth. The earth does not give up its wealth without teaching something of its laws. This knowledge may not be so extensive, so precise or so well organized as that which we at present call scientific. But it has one high mark of truth. It works. Which means that within important limits it is true. Moreover, if not so extensive as science, it is generally more intensive. It is less knowledge than practical wisdom. Such as it is, it is the subsoil out of which all higher forms of culture grow.

To a sufficiently superficial view, the most essential requisite of this industrial civilization appears to be machinery, for it is only by machinery that men are able to control indefinitely great force with indefinitely great precision, and so to gain their indefinitely great ascendency in the world. The smallest penetration shows, however, that the one essential machine by which all other machines have been made, and for which all other machines are supplements, is the nerve-muscle apparatus. The bare-handed man has at disposal comparatively little force. He can manipulate this force with comparatively little precision, either in space, in time or in intensity. He has accordingly comparatively little freedom; comparatively small ability to modify his environment and to help determine his own course therein. Much or little, however, this power and skill and consequent freedom are the fundamental capital of life. All greater powers through machines, all finer skills, through instruments of precision, all larger freedoms up to the highest which men enjoy, have their essential pre-condition and their prototype in the howsoever modest attainments made in the individual body. When, besides, it is remembered that the life-long and world-long expression of thoughts and feelings solely through muscular movements makes muscle habits infinitely the most subtle and complete record of the conscious life, and when it is remembered, further, that these muscle habits constantly react with deter-

mining power upon the whole activity and growth of the mind, it is not enough to say that the subject is entitled to study from the standpoint of Psychology and the History of Culture. It must rather be said that these sciences will be obliged to study the development of motor ability. We have a right to expect from such study a typical chapter in the whole progress of man, a "grammar of will." And we have therefore a right to hope from such study new and fundamental approaches to the understanding of the History of Culture.

Inasmuch as voluntary motions are data at once for Physiology, Psychology and the History of Culture, one might expect to find that they had already received attentive study from all, or at least from some, of these standpoints. In fact, however, the point of common interest has been a point of common neglect. Students of the History of Culture have found overwhelmingly abundant material for research and speculation in the results,—the records of human reaction upon the world—tools, buildings, works of art, languages, books, rites, governments, etc. They have accordingly been able to overlook the muscular motions through which alone these "works" have arisen. The manifest importance of the sociological material, moreover, has made muscular motions, as such, seem comparatively elementary and trivial. It may accordingly be understood why it is only in rare instances — as in one department (phonetics) of the old and highly developed science of philology — that we have any considerable study of muscular motion.

If the study of voluntary motion has been postponed in Sociology because of its simplicity, it has been postponed in Physiology for just the opposite reason. "Man kann behaupten," says Fick, "dass die ganze thierische Organization jene ('willkürliche') Bewegungen zum Zwecke hat" (35). But of the "riesiges Material von Versuchen über Muskelzusammenziehung," of which he speaks (p. 2), nearly all is engaged with the more elementary phenomena of nerve-muscle action rather than with what von Kries calls "resultirende Bewegungen." Von Kries says (3):

"Einer Untersuchung der willkürlichen Muskelthätigkeit bieten sich wesentlich zwei vershiedene Aufgaben, welche, wiewohl in naher Beziehung zu einander, doch sorgfaltig unterschieden werden müssen. Wir können zunachst die Bewegungen beobachten welche sich an den festen (knöchernen) Theilen des Körpers durch willkürliche Muskelthätigkeit hervorbringen lassen; wir wollen sie kurz die resultirenden Bewegungen nennen. Da es shon bekannt ist, dass diese

Bewegungen in der Regel durch ein verwickeltes Zusammenwirken vieler Muskeln bewirkt werden, so erhebt sich als weitere Frage die nach der Thätigkeit der einzelnen Muskeln. In dieser letzen Hinsicht steht seit geraumer Zeit die Frage nach gewissen zeitlichen Verhältnissen insbesondere nach der Stetigkeit oder Discontinuität, eventuell nach dem Rhythmus der Innervation, im Mitteltumkt bes Interesses, ohne jedoch bis jetzt abschliessend beantwortet zu sein. Aber auch in der ersteren bieten sich gewisse einigermaassen ähnliche Fragen welche mir ein selbständiges Interesse zu verdienen scheinen."

The efficiency of a machine depends, so far as we know, upon the maximum force, rate, amplitude, and variety of direction of its movements; and upon the exactness with which, below these maxima, the force, rate, amplitude and direction of its movements can be controlled. The motor efficiency of a man depends upon his ability in all these respects. All of them are determinable within varying limits of precision. All of them have been made objects of research more or less limited. But an adequate determination in respect to any of them, either for the average adult, for children at successive stages of development, or for the sick or aged in in successive stages of decline, is wanting.

The following research deals with the development of voluntary motor ability of children with respect to

1. The maximum rate of rhythmically repeated movement.
2. The precision of voluntary movement, particularly as regards direction and force.
3. With a note on the bilateral development of strength and endurance.

The Maximum Rate of Voluntary Movement.

LITERATURE.

1. *The maximum rate of inervation.*

The maximum rate of inervation has been reported differently as follows:

Helmholtz(4), 1866, 18–20 per second.
Hall and Kronecker(5), 1879, about 20 " "
Horsley and Schaefer(6), 1886, 10 " "
Schaefer, Carney and Turnstall(7), 1886, 8–12, Av. 10 per sec.
Von Kries(3), 1886, 11–12.4 per second.
Griffiths(8), 1888, 8–21 per second (see below).
Haycroft(9), 1890, about 19.5 " "

H. thinks that the muscle vibrations "cause and compound themselves" with rhythms in the instruments used, and so endeavors to explain former contradictory results.

2. *The Maximum Rate of "Resulting Movements."*

Von Kries([7]).

Shortest movement of middle finger (Av. 11 trials), .077.
Hand, (Av. 10 trials), .074.
Tongue, .066.
Foot (plantar flexion), .125″–111″.
Jaw, 125″–111″.

Maximum rate of rhythmically repeated movement after practice, 10–11 per second.

Vocal organs about same as hand.

Respiration in dogs has been observed at 7 per second.

Cattel and Fullerton([10–1892]), for a movement of 50 cm. time varies from 87″ to 118″ in four individuals.

Dresslar([11–1892]) (when 300 taps were made), 6.5–10.5 per second.

For a short time, 11 per second.

Dresslar gives the records of 27 adults. The average of these records is about 6 per second; 300 taps were made in each case.

3. *Influences Affecting the Rate of Movement.*

Horsley and Schaefer([5]). The rate of the muscle rhythm is the same when cortex or spinal centers are electrically stimulated and when the muscle is voluntarily stimulated.

Griffiths([8]). The rate of voluntary muscle rhythm varies in different individuals, different muscles, and with fatigue.

Dresslar([11]). Muscular exercise lowers the rate; mental excitement increases the rate. There is a daily rhythm with the rise and fall of mental and nervous tension.

Cattell and Fullerton([10]). Women have decidedly slower rate than men. The rate is very constant.

Von Kries([7]). The rate varies slightly in different muscles; increases with practice; but is not affected by variation of the amplitude of motion within wide limits, a certain medium amplitude requiring less time than longer or shorter distances.

(See v. Kries' tables (op. cit. p. 4), where it is shown that excursions of 10 mm. and 16 mm. are made by the middle finger in less time than are excursions of 4 mm.; that excursions of 19 mm. and 25 mm. are made in less time by the hand than are excursions of 9 mm.; and that a decided increase in time over that required for excursions of 4 mm. or 5 mm. does not appear in excursions of less than 30 mm.)

Camerer([12]), 1866.

The will brings about an intended rate of movement only gradually. Constant rate of motion is unnatural and forced. The natural rate of motion is one of constant acceleration.

Conclusions from the Literature.

The maximum rate of voluntary muscle rhythm is not satisfactorily determined.

The maximum rate of voluntary rhythmically repeated "resulting movements" in adults has been found in some cases 11–12 per second. The average maximum rate of adults is not determined.

The maximum rate varies with individuals, with muscles used, with fatigue, and with mental excitement; but not within wide limits, with the amplitude of the movement.

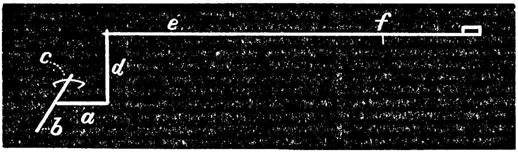

FIG. 1.—Scheme of Mechanical Counter.

Apparatus (see Fig. 1). A spring clock movement (cost $1.00) was taken out of its case. The balance wheel with its spring was removed. The axle (b) which supports the escapement lever (c) had rigidly attached to it, and extending about four mm. horizontally from it, and at right angles to it, a strip of brass (a). The outer end of this strip was fastened to a light wooden lever (e). The attachment between the two was made by means of another strip of brass (d) about 5 mm. long, fastened to each by fine flexible wire loosely enough to allow necessary play. The fulcrum (f) of the lever, distant about 34 mm. from the clock, was supplied by a Morse key, the arm of the key forming a rigid continuation of the lever attached to the clock. The key and the clock were each firmly fastened to the same wooden base at a distance determined by the length of the lever. The end of the lever attached to the clock, was made to occupy a position directly above its point of attachment, at a distance determined by the length of the connecting strip. This distance demands rather delicate adjustment, in order that the upward and downward movements of the lever may cause a properly balanced upward and downward movement of the escapement lever. When proper adjustment is made, taps upon the button of the Morse key permit the 'scape wheel to revolve, one cog and only one, for each tap. To prevent possible errors in the train of wheels connecting the escapement and the second hand, a hand was attached to the axle of a second's wheel, which engages directly with the 'scape wheel, the clock face being secured in a corresponding position. It requires 120 taps to permit the hand to make one revolution.[1]

[1]There are 48 cogs on the second's wheel engaging with 6 cogs on the axle of the 'scape wheel. There must therefore be eight revolutions of the 'scape wheel to permit one revolution of the second's wheel. And since there are 15 cogs on the 'scape wheel, there must be 8 x 15 escapements in order that the second's wheel may revolve once.

The distance through which the button of the Morse key must be moved depends of course upon the length of the lever employed. The maximum vertical movement of either pallet of the escapement lever, in the clock used, is 1.5 mm. The depth of the cogs of the 'scape wheel is 1.1 mm. The distance from weight to fulcrum, and from fulcrum to power, being 34 mm. and 9 mm. respectively, the minimum and maximum movements at P must be respectively .29 mm. and .39 mm. The amount of force required is insignificant.

The accuracy of the apparatus was tested by placing the Morse key in a circuit with a Duprez signal, in position to write upon the kymograph. It was found in many trials that the number of taps recorded upon the clock face corresponded with the number of taps recorded upon the drum. An (undescribed) apparatus devised by Dr. E. C. Sanford, differing from that described in that the lever is attached to the armature of a magnet and moved to and fro by the counter action of an electric current and spring, was tested by the Kronecker interrupter and proved correct to 20 counts per second. As the two devices are essentially the same, except in the mode of moving the lever, this test indicates the probable capacity of the instrument used by me. A few of the measurements hereafter described were made with Dr. Sanford's apparatus.[1]

THE COURSE OF THE EXPERIMENTS.

All the joints of the upper extremities were tested. The conditions of the tests were as follows:

Shoulder.

The forearm being held at right angles to the upper arm, and the back of the elbow being held in position above the button of the Morse key, the upper arm was caused to move up and down as rapidly as possible in a plane nearly parallel with the vertical plane of the body, i. e., in about that plane in which the arm tends to swing when one walks.

Elbow.

The elbow rested upon the table. The forearm was held at right angles to the upper arm. The key was struck with

[1]The use of reaction time as a general clinical test has, it is well known, been made difficult by the cost of apparatus and by the delicate manipulation required to secure reliable results. If it should prove true, as now seems probable, that the rate of voluntary movement is a valuable supplement to the reaction time test—if not also in many cases a good substitute therefor—these difficulties will not be met. The apparatus which I have described, for example, can be made at a cost of two or three dollars and will give reliable results without more time or care in manipulation than many clinical tests in general use require.

the ventral side of the forearm just back of the wrist. In a few instances the arm was extended and while the elbow rested upon the table, as before, the taps were made with the little-finger side of the wrist. No difference appeared in the rate of the two motions. It is to be noted that the school experiments were made with the ordinary (Spring) clothing about the arm. In my own case, the removal of my coat made no discernible difference in the rate of elbow or shoulder, owing, I think, to the great disproportion between the force of the limb in movement and the resistance which ordinary clothing presents.

Wrist.

The elbow rested upon the table. An iron clamp, whose jaws were covered with firm cushions of cloth over cotton, was placed rather loosely about the forearm just back of the wrist joint, and was held in position by an ordinary stative. The key was struck with the palm of the hand.

Metacarpo-Phalangeal Joint of Forefinger.

The palm of the hand was held with moderate firmness at an angle of about 135° with the forearm. The finger in position was then nearly or quite parallel with the forearm. In this way possible sympathetic movements of the wrist were prevented from affecting the record. If properly placed, the clamp does not interfere in the least with free movement of the finger. Other phalangeal joints were tested only in the case of adults. A narrow clamp was then used and, as in the case of the hand, interference with other joints was prevented in part by the position in which the member was held.

In all the experiments reported in this paper, the maximum number of taps in five seconds was determined, and all results are given in terms of x taps in five seconds. A stop watch, or rather a timer, measuring fifths of a second, was used to measure the time. In 60 seconds this timer shows no discernible variation from a standard second's pendulum. For measuring periods of five seconds, therefore, the readings do not differ from those which could be obtained from a theoretically perfect instrument.

In the case of adults, the subject, being in proper position with reference to the tapping apparatus, and with the timer before him, began to tap as the watch hand passed a five-seconds mark upon the dial, and ceased tapping as the hand passed the next five-seconds mark. It is obvious that each time, the personal errors at the beginning and at the end of the interval tend to balance each other, and that, in the long run, the plus and minus errors in this balance tend to balance each other. In the school experiments the starting and stopping followed a word of command. The timer was

started as nearly as possible at the same instant in which movement was observed to begin. When five seconds had elapsed the command to stop was given and any subsequent tap was not counted. The reaction time of the pupil was thus not included, and the observer's errors tend to balance as above. The error from this source can scarcely exceed one tap in a single test.

To prevent incipient fatigue, slight pauses were made between each five-second period of work, with longer pauses every second or third time.

All the rate tests were taken by myself, except possibly a dozen taken by my wife, who assisted me throughout every part of the present research, and who was thoroughly familiar with every detail of the work.

Preliminary Experiments.

Besides furnishing a test of the apparatus and method used, the preliminary experiments upon adults show some important characteristics of the rate of voluntary motion.

1. The rate of voluntary motion in a given joint of a given individual is very constant.

The following tables taken at random from many, show the degree of variation in individual successive measurements.

(Explanation of tables: I., outer joint of the forefinger; II., middle joint of forefinger; III., metacarpo-phalangeal joint of forefinger; IV., wrist; V., elbow; VI., shoulder; VII., free tap. Each number in the tables shows the number of taps made in a period of five seconds.)

Table I. Subject, L. B. February 18, 1892.

	I	II	III	IV	V	VI	VII
Right.	27 26 28 28 32	28 27 30 27 30	35 35 35 33 36	37 34 34 38 35	34 33 33 34 33	33 29 29 29 34	34 38 38 35 34
Left.	27 31 27 26 28	26 28 26 28 28	31 30 29 30 30	34 36 35 33 34	31 32 34 36 34	25 25 25 26 25	38 31 35 32 33

SUBJECT, E. C. S. FEBRUARY 27.

	I	II	III	IV	V	VI	VII
Right.	19 17 26 23 22	30 29 22 25 29	30 30 28 30 30	39 37 37 36 34	35 32 27 37 30	32 24 29 25 27	38 43 41 39 37
Left.	16 17 17 18 16	18 16 17 15 18	26 25 23 26 23	27 25 25 27 24	24 29 21 22 23	22 18 21 17 18	26 31 27 30 27

SUBJECT, W. B. FEBRUARY 29.

	I	II	III	IV	V	VI	VII
Right.	23 23 23 22 22	23 22 23 23 21	25 24 23 27 24	29 27 23 30 27	39 41 40 37 39	28 30 20 28 28	36 38 36 40 39
Left.	17 15 15 11 11	15 16 18 18 17	20 20 20 22 23	20 21 21 24 23	24 23 27 25 25	17 22 21 17 23	27 26 24 24 26

Mean Variation of Individual Results from the Mean.

In the case of 239 mean rates, each obtained from five single tests on W. B., the mean value of the mean individual variations $\left(\frac{\Sigma v.}{n}\right)$ is .85 taps in five seconds; and two thirds of the $\left(\frac{\Sigma v.}{n}\right)$ values are less than 1.1 taps in five seconds. In 82 such mean rates obtained from L. B., the mean value of $\left(\frac{\Sigma v.}{n}\right)$ is 1.09 taps in five seconds and two thirds of these $\left(\frac{\Sigma v.}{n}\right)$ values are less than 1.4 taps in five seconds. Of 355 mean rates obtained from three subjects, 96% show $\left(\frac{\Sigma v.}{n}\right)$ values less than two taps in five seconds. So far as these experiments have

weight accordingly, the probability is .96 that two records of the maximum rate of voluntary movement, taken as nearly as possible under the same outer and inner conditions, will differ less than two taps in five seconds. It is altogether likely that there are individuals in whom the variability would be somewhat greater.[1]

2. The rate of voluntary movement undergoes slight and gradual but measurable changes due to changes in the subject.

Effects of Local Cold. The application of snow to the left forefinger resulted in reductions of the rates of the joints of that finger, amounting to 1.6, 1.6 and 1.4 taps in 5″; but caused no corresponding change in the rates of the other joints.

Effect of Local Fatigue. Fatigue was induced by rapid and continuous voluntary movement of the joint, in the same manner as that required in tapping with that joint. Sometimes fatigue was hastened by weighting the joint. Tests were taken from time to time after ten minutes' work. The final tests were taken after one to three hours' work. In one case (Table III.), fatigue was induced in the left hand by gripping upon the Galton dynamometer. In all cases the process becomes excessively painful. Following tables give the results gained. Explanation of tables : The joints are indicated by the Roman numerals from I. to VI., beginning with the outer finger joint. VII. indicates the free tap. R=Right side. L=Left side. The exponent a means that the series following was taken before fatigue. The exponent w indicates that every single record represented in the series of averages following was taken while one of the joints upon that side was in state of extreme fatigue. The exponent b indicates that every single record represented in the series of averages following was taken while one of the joints upon the opposite side was in a state of extreme fatigue. The wearied joint and the corresponding joint on the other side are indicated by underscoring their records. The records of other joints upon both sides are given to show the general motor ability before and during the local fatigue. For convenience of reference, each set of results has been numbered. In (33) a was taken at the point

[1]The constancy of the maximum rate of motion is indicated by the small limits within which the racing records of a given individual vary. Notwithstanding the very large number of motions made by a horse in running one mile, a dozen successive race-records are not expected to have a gross variation of more than two or three seconds, if the horse, the track, the weather, etc., are each time in about the same condition. The same holds true of bicycle riders, oarsmen etc.

of extreme fatigue, b after an interval of recovery. In (36 and 38) a, b, c, and d were taken in order at various periods from thirty minutes to two and one-half hours. In (42) a, b and c were taken at periods of fifteen, forty-five and one hundred and fifty minutes, work being continued all the time.

TABLE II.

RATE OF TAPPING. I. P. 1–6. RECORD W. B.

	I	II	III	IV	V	VI	VII	No.
Feb. 2, R^a	22.6 .4	22.4 .7	24.6 1.1	29.6 1.8	39.2 1.1	28.6 .6	38. 1.4	1
" 2, R^b	20.2 .3	19.8 .7	23.2 .2	28.8 1.	35.4 1.6	26.2 1.7	38.8 .6	2
" 2, L^w	13.4 1.9	16.6 .9	21. .6	21.4 .9	24.8 .1	20.6 1.6	25.4 1.9	3
" 5, R^a	19.2 .7	22.2 .6	29.6 .9	33. 1.1	37.2 .3	31. 2.8	40. 1.6	4
" 5, R^b	18.4 .6	19.6 .5	22.8 1.0	28.4 1.2	34 8 .9	30.2 1.8	38.2 1.	5
" 5, L^w	18.4 .6	18.2 .7	18.8 1.	21.4 1.1	27.4 .9	23.8 1.4	25.8 1.	6
" 8, R^a	21. .4	22.6 1.1	26.6 .5	31.4 1.9	35.8 1.4	28.8 1.4	38. .8	7
" 8, R^b	21. .8	20.6 1.7	26. .4	28.4 2.	34. .2	30.2 1.	36.2 .6	8
" 8, L^w	19.4 1.	18.6 .6	22. .8	23.8 .6	27.2 1.5	27.4 1.1	28.2 1.4	9
A.M. " 9, R^a	19.8 .3	19.2 1.7	25.6 1.2	31.8 1.7	38.2 2.	28.4 .9	38.6 1.1	10
" 9, R^b	20.2 .5	19.6 .9	27.2 .7	30.8 .7	30.2 .2	29.4 1.1	33. 2.4	11
" 9, L^w	18.6 .9	19. .4	22. 1.2	25.8 1.1	23.2 1.	25.2 1.	25.6 .9	12
P.M. " 9, R^a	20.8 1.	21.8 .6	26.8 1.4	29.4 1.0	34.8 .6	29.2 1.	36.8 1.1	13
" 9, R^b	21.3 .2	21. 1.2	26.6 .7	29.6 .5	31.8 1.4	25.8 1.4	36.2 .6	14
" 9, L^w	18. .4	20. .8	22.4 .8	25. 1.2	25.2 .3	20.6 1.1	25.8 1.0	15
A.M. " 11, L^a				24.8 .8	26.6 .5	21.4 1.4	27.4 .9	16
" 11, L^b				23.0 .8	24.1 .2	21.6 1.1	25.8 .6	17
" 11, R^a				33. .8	35.6 1.9	27.6 1.1	37.4 1.7	18
" 11, R^w				30.6 .6	28.8 1.7	26.4 .5	30.2 2.1	19
P.M. " 11, L^a			23.6 .5	25.2 .3				20
" 11, L^b			21.3 .6	23.9 .5				21
" 11, R^w			21.0 .5	31. .1				22

TABLE II.—*Continued.*

RATE OF TAPPING. RECORD W. B.

	F. Finger.			M. Finger.			R. Finger.			L. Finger.			Thumb.			
Feb. 10	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	
R^a	22.6	22.6	25.8	21.6	23.2	26.4	20.2	20.6	24.8	20.	20.4	24.8	20.6	21.	23.8	23
	1.1	1.1	.6	1.3	.3	.9	1.1	1.3	.3	1.2	1.1	.6	1.6	.8	.6	
L^a	18.8	20.4	22.4	13.2	17.8	22.	12.4	17.2	19.6	13.4	16.2	18.	17.8	16.4	18.6	24
	.6	.3	.5	.6	.6	.4	.7	.3	.9	.9	.1	.8	.6	.5	1.3	
L^b	17.4	18.4	19.2			21.6			20.2			18.6			20.	25
	.5	.1	1.			.6			.3			.9			1.2	
R^w	22.2	21.6	24.6			26.			24.2			22.6				26
	.7	1.5	.8			.8			.7			.7				

RATE OF TAPPING. RECORD W. B.

Feb. 17	I	II	III	IV	V	VI	VII		
R^a	21.2	21.2	25.8	32.6	37.8	27.4	38.		27
	.7	.6	.3	1.4	.7	1.4	1.2		
L^a	18.	18.8	23.4	24.2	27.	22.	26.6		28
	.5	.6	.5	1.9	.4	.4	.7		
R^w			25.8	32.6	32.2	26.4	36.8		29
			1.	3.6	1.4	1.3	2.5		
L^b			22.4	23.	25.	23.	26.		30
			1.1	.8	.8	.4	.4		

RATE OF TAPPING. L. B. RECORD.

Feb. 17	I	II	III		IV	V	VI		
Left A.	23.2	25.6	30.8		31.6	31.6	25.2		31
	1.4	1.7	1.9		3.	.8	.7		
R^a	24.6	26.1	34.3		36.	35.3	31.6		32
	.6	1.6	.4		.2	1.0	.7	A's taken first. B's after an interval of recovery.	
	B	B			B	A	*B*		
R^b	27.2	28.	29.4	31.6	34.8	34.8	30.		33
	1.4	.8	1.2	1.3	1.	.7	1.2		
	B	*B*	A	*B*	*B*	*B*	*B*		
L^w	26.	27.1	25.7	29.8	33.4	32.2	26.2		34
	.4	1.4	.3	1.3	1.4	2.1	1.6		

TABLE II.—*Continued.*

RATE OF TAPPING. RECORD F. B. D.

Feb. 18 7 P. M.	I	II	III	IV	V	VI	VII	
R^a	21.6	30.	38.1	55.2	44.	26.	61.8	35
	.4	1.3	.5	4.1	3.8	1.2	.6	
R^b	20.	33.3	(a) 54.	50.	49.	26.	58.5	36
	0.	.3	5.3	0.	1.	0.	1.	
			(b) 52.3					
			3.9					
			(c) 50.6					
			3.					
			(d) 50.6					
			.3					
L^a	19.	24.2	37.6	40.6	38.	24.	41.	37
	0.	.7	1.	1.3	2.5	.6	2.	
L^b	20.6	25.	(a) 29.3	41.	34.	25.	42.	38
	.8	1.	2.4	1.	.6	0.	2.	
			(b) 30.2					
			5.2					
			(c) 30.7					
			.7					
			(d) 34.					
			1.7					

RATE OF TAPPING. RECORD E. C. S.

Feb. 27	I	II	III	IV	V	VI	VII	
R^a	21.	27.	30.7	36.4	32.8	27.4	39.6	39
	2.6	2.8	2.2	1.2	1.7	2.5	1.9	
L^a	16.8	16.8	24.8	25.6	23.8	19.2	28.2	40
	.6	1.	1.3	1.1	2.1	1.8	1.8	
R^b	23.4	25.4	27.3	37.4	45.*	26.	40.8	41
	2.1	1.8	1.2	1.3	6.4	2.2	1.4	
L^b	16.2	18.6	(15 m.) 20.8	26.8	24.2	21.6	29.4	42
	.3	.6	.6	1.	1.8	2.	1.9	
			(45 m.) 19.8					
			.6					
			(2½hrs.) 18.4					
			1.2					

*The individual rates were 54, 39, 39, 50, 38. The 54,50 rates were visibly the shiver of "voluntary tetamus."

TABLE III.

RATE OF TAPPING. WEARYING BY GRIP OF LEFT. W. B.

	I	II	III	IV	V	VI	
R^a	21.	23.	25.	28.	34.	32.	43
R^b	21.	24.	25.	28.	38.	30.	44

1. Fatigue begins to show itself by a perceptible lowering of rate after ten or fifteen seconds' work.

This fact appeared so clearly that it proved necessary to allow a brief interval of rest between each five-second period of work, and longer intervals every second or third time.

(NOTE—See in Dresslar's Influences affecting Rate, the evidence of fatigue in the course of 300 taps.)

2. After ten to fifteen minutes' work the reduction in rate is considerable. Thereafter the reduction goes on more slowly. By three hours' work E. C. S. reduced his left wrist to momentary helplessness.

3. Partial recovery takes place very quickly.

This fact came out with such certainty that it proved necessary to keep the wearied joint hard at work throughout the series except during the 5″ intervals when a test was in progress.

4. Complete recovery from excessive fatigue takes place slowly.

Compare Nos. 10-12 with 13-15, Table II., for evidence of the persistence of fatigue during 2-4 hours' rest.

5. Working a joint induces a local fatigue, which does not perceptibly affect the rate of remote joints. In some cases the fatigued joint's rate is reduced, while nearly all the other joints show an increase of rate.

6. Taking the average yearly increase of rate as a standard, the change of rate induced by fatigue is very great.

It will be shown later on, that between the ages 6 and 16 the average yearly increase of rate ranges from .74 to 1.44 taps in five seconds, and that a yearly gain of two taps or over in five seconds has a probability of .17 or .33 less than an even chance. The decrease of rate by local fatigue induced by 1 to 2½ hours' hard work is shown to be as follows:

W. B., 5, 4.6, 6.8, 1.2, 5.6; L. B., 5.1; F. B. D., 8.3; E. C. S., 5.

As noted above, by 3 hours' work, E. C. S. reduced the rate of the left wrist practically to zero.

In all but one instance these amounts are equivalent to the growth of three or four years.

7. I am not prepared to say positively whether local fatigue in a joint affects the rate in the corresponding joint on the other side. The facts are as follows: In my own case (as shown in the W. B. records) in every trial (left shoulder, elbow, wrist, hand-finger joint and middle finger joint; and with the right elbow, wrist and hand-finger joint), extreme local fatigue in a joint was followed by a diminution in the rate of the corresponding joint on the other side, while other joints, upon both sides, showed no corresponding change in general motor ability.

As results in which the experimenter is the subject, are always justly subject to doubt because of the possible unconscious influence of expectation, I observe,

(a) In Table III., where it is shown that wearying the left hand by gripping was followed by no discernible change in rate of any right side joint, the contrary result was fully expected.

(b) In my case, the most rapid joint is the elbow. The rate of the free tap is, therefore, mostly determined by the rate of the elbow. It will be seen in each case that the rate of elbow and free tap closely agree. If, now, those cases in which either elbow was wearied be examined, it will be seen not only that the rate of the other elbow is lowered, but also that the rate of the free tap on the other side was lowered. This result was not anticipated, and only came to notice when calculations and comparisons were made subsequent to the conclusion of the experiments.

(c) On February 9th, A. M. (Table II., 10-12), the left elbow was wearied, the experiment concluding about noon. At about 2 P. M. of the same day work was resumed, the left shoulder being wearied. The record for February 9th, P. M. (Table II., 13-15), shows that neither the left elbow fatigued in the morning nor the right elbow have recovered their normal rate, although the rate of other joints proves that there was no general decline of motor ability. This result was not anticipated and was not discovered until later.

The results from L. B. confirm the results from W. B.

The results from F. B. D. show an extraordinary increase in the rate of the joint corresponding to the wearied joint, in the presence of no considerable change in the rate of other joints on either side. This wholly unexpected result was thoroughly verified.

The results given from E. C. S. appear to confirm the result from W. B. In a second very thorough trial, the left wrist being fatigued to the point of temporary helplessness,

no bilateral effect appeared. I have had the misfortune to lose this valuable negative record. I have been strongly inclined on this account to withhold all results on this point from publication. I have concluded to publish the results, specially emphasizing the entirely negative result from E. C. S. and withholding, until further investigation, any positive conclusions as to the question involved.

The Effect of Amplitude of Movement on Rate. I have already referred to the conclusion of von Kries (p. 138), that "the extent of the movement has small influence upon its duration," motions of a certain medium extent appearing to be carried out more quickly than longer or shorter ones. With this result my observations are in entire agreement. The following table gives the number of double excursions of the several amplitudes indicated in five seconds:

TABLE IV.

Extent of Excursion in mm.	1	5	10	15	20	25	30	40
Number of double excursions in 5 sec.	27	26	27	30	30	30	25	20
	28	29	28	30	29	30	26	23
	24	28	28	29	30	30	24	24
	24	29	30	28	30	29		26
	27	32	29	31	31	28		
	27	29						
	25							
Average.	26.	28.8	28.4	29.6	30	29.4	25	23.2

Maximum Rate of Tapping by Adults. A sufficient number of adults have not been tested to permit the establishment of a normal mean rate or to show the individual variation. For the results with unwearied joints see Table II. Nos. 1, 4, 7, 10, 13, 16, 18, 20, 23, 24, 27, 28, 31, 32, 35, 37, 39, 40 and 43.

SCHOOL EXPERIMENTS ON RATE.

(NOTE—I am indebted to Superintendent Marble and the school authorities of Worcester, and to Dr. Franz Boas, for the opportunity of making these tests.)

Seven hundred and eighty-nine school children of the City of Worcester, Mass., ranging in age from 5 to 16 years, were tested with the apparatus and by the method described. The shoulder, elbow, wrist and metacarpo-phalangeal joint of the forefinger on each side were so tested.

Classification of Results.

Forty-six individuals (twenty-six boys and twenty girls) were more or less left handed. Their records are taken account of separately (175). Twenty individuals (fourteen boys and six girls) of five years of age were tested. The boys' record is printed in Table VI. The principal calculations and results of this paper refer to the 723 right-handed individuals ranging in age from 6 to 16. The 5,784 single results obtained from these individuals were classified according to the age and sex of the individual, and according to the side and joint used.

Method of Treating Results.

The several results belonging to each class,—for example, to the right finger of the boys of six,—were tabulated so as to show the different rates found in that class (Column I.), (Table V.page 152) and the number of times each of these rates occurs (Column II.). Each rate found was multiplied by the number of times it occurs ; and the sum of these products (Column III.) was divided by the sum of individual cases. The differences between this result, the arithmetical mean, and each rate found were taken (Column IV.), and these residuals were squared (Column V.). Each squared residual was multiplied by the number of times the corresponding rate occurs. The sum of these weighted squared residuals (Column VI.) was divided by the number of individual cases. The square root of this quotient is the mean individual variation, showing the limits of distance from the mean, within which 68.3% of the individual results fall. This individual mean variation divided by the square root of the number of cases, gives the mean variation of the mean. The probability is .683 that the true mean lies within the limits thus determined.[1]

The tabulation and calculation for boys' right finger, 6, are given as an example. A designates the arithmetical mean ; μ the mean individual variation and μ_0 the mean variation of the mean. The values of A, μ, and μ_0 for each class, are given in Table VI. page 152, andare represented graphically in chart I. In the latter the values of A are connected by

[1] The so-called probable errors, i. e., the errors whose probability is. 50, may be found by multiplying the values of μ and μ_0 by .6745.

solid lines, and the values of μ and μ_0 by dotted lines on each side of the solid line.[1]

TABLE V.

RATE BOYS 6. RIGHT FINGER. n=26.

Rates found = R.	No. of cases at each rate = n.	R x n.	Residuals. = v.	v^2	n $v.^2$
I	II	III	IV	V	VI
15	1	15	4.5	20.25	20.25
16	1	16	3.5	12.25	12.25
17	1	17	2.5	6.25	6.25
18	4	72	1.5	2.25	9.00
19	3	57	.5	.25	.75
20	10	200	.5	.25	2.50
21	3	63	1.5	2.25	6.75
22	2	44	2.5	6.25	12.50
23	1	23	3.5	12.25	12.25
	26	507			82.50 $=\Sigma$ v.^{2}

507÷26=19.5=A.

$$\sqrt{\frac{82.50}{26}}=1.78+=\mu_R$$

$$\frac{1.78}{\sqrt{26}}=.34+=\mu_{OR}.$$

[1] It must be kept in mind that the mean rates do not represent quantities which exist in nature. Each mean is a function of the individual rates found in a given class, and only in connection with the mean individual variation and the mean variation of the mean itself, does it represent the probable rate and distribution of rates for that class.

TABLE VI.

RATE: AGE 5.

		Boys, n=14.			Girls, n=6.
		A	μ	μ_o	Omitted, because so few.
R	F	19.6	2.82	.8	
	W	20.1	3.66	1.0	
	E	22.7	2.90	.8	
	S	18.4	2.72	.7	
L	F	17.3	3.34	.9	
	W	17.	3.39	.9	
	E	18.2	3.23	.9	
	S	17.	2.38	.6	

RATE: AGE 6.

		Boys, n=26.			Girls, n=28.		
		A	μ	μ_o	A	μ	μ_o
R	F	19.5	1.78	.3	19.8	2.56	.5
	W	23.	2.72	.5	21.6	2.57	.4
	E	23.5	1.45	.3	22.7	2.33	.4
	S	19.8	2.81	.6	19.9	2.71	.5
L	F	18.	1.56	.3	18.	2.76	.5
	W	19.7	2.32	.5	18.9	2.33	.4
	E	20.4	2.47	.5	19.7	2.06	.4
	S	18.2	2.34	.5	17.9	2.43	.5

RATE: AGE 7.

		Boys, n=35.			Girls, n=32.		
		A	μ	μ_o	A	μ	μ_o
R	F	21.	2.64	.4	20.7	2.46	.4
	W	23.7	2.91	.5	23.1	2.7	.5
	E	24.2	3.71	.6	23.2	1.95	.3
	S	20.5	2.48	.4	20.2	2.66	.5
L	F	19.1	2.4	.4	19.1	3.23	.6
	W	20.2	2.6	.4	20.	2.46	.4
	E	20.9	3.07	.5	21.5	2.96	.5
	S	18.8	2.5	.4	18.8	2.67	.5

TABLE VI.—*Continued.*

RATE: AGE 8.

		Boys, n=33.			Girls, n=32.		
		A	μ	μ_o	A	μ	μ_o
R	F	23.1	2.56	.4	22.2	2.74	.5
	W	26.3	2.83	.5	24.3	2.73	.5
	E	26.1	2.57	.4	24.4	2.68	.5
	S	22.3	2.26	.4	21.9	3.08	.5
L	F	20.5	1.91	.3	19.7	2.71	.5
	W	22.2	2.88	.5	21.	2.69	.5
	E	22.3	2.61	.4	21.6	2.27	.4
	S	20.2	2.69	.5	20.2	2.64	.5

RATE: AGE 9.

		Boys, n=43.			Girls, n=36.		
		A	μ	μ_o	A	μ	μ_o
R	F	24.4	4.15	.6	24.	2.69	.4
	W	27.8	3.5	.5	25.5	3.26	.5
	E	28.2	3.52	.5	25.4	3.62	.6
	S	24.1	3.65	.6	22.7	3.26	.5
L	F	21.5	3.6	.5	20.6	2.92	.5
	W	23.6	3.84	.6	22.4	2.99	.5
	E	23.8	3.67	.6	22.6	2.91	.5
	S	20.9	3.57	.5	20.8	3.79	.6

RATE: AGE 10.

		Boys, n=37.			Girls, n=35.		
		A	μ	μ_o	A	μ	μ_o
R	F	25.2	2.29	.4	25.8	3.36	.6
	W	28.5	3.34	.5	28.5	3.66	.6
	E	28.1	3.60	.6	27.5	2.96	.5
	S	22.6	2.75	.4	22.6	2.76	.5
L	F	22.4	3.15	.5	22.3	2.64	.4
	W	24.5	3.70	.6	24.3	2.42	.4
	E	24.7	2.74	.4	24.	2.51	.4
	S	20.5	2.85	.5	21.6	2.62	.4

TABLE VI.—*Continued.*

RATE: AGE 11.

		Boys, n=36.			Girls, n=35.		
		A	μ	μ_o	A	μ	μ_o
R	F	27.	3.60	.6	27.1	3.44	.6
	W	30.3	4.62	.8	30.4	4.30	.7
	E	29.3	3.41	.6	28.6	3.44	.6
	S	24.1	2.93	.5	24.9	3.30	.6
L	F	23.9	2.57	.4	24.9	3.48	.6
	W	25.9	3.69	.6	26.3	4.02	.7
	E	26.	3.41	.6	26.2	3.57	.6
	S	21.5	2.57	.4	23.6	3.44	.6

RATE: AGE 12.

		Boys, n=33.			Girls, n=34.		
		A	μ	μ_o	A	μ	μ_o
R	F	29.3	5.4	.9	28.2	3.98	.7
	W	31.6	5.27	.9	31.6	5.18	1.0
	E	29.9	4.12	.7	29.4	4.90	.8
	S	25.	3.32	.6	25.7	4.35	.7
L	F	26.3	3.84	.7	25.8	3.44	.6
	W	26.9	3.70	.6	27.	4.90	.8
	E	26.3	3.76	.6	26.2	4.56	.8
	S	22.4	3.59	.6	23.6	3.64	.6

RATE: AGE 13.

		Boys, n=34.			Girls, n=34.		
		A	μ	μ_o	A	μ	μ_o
R	F	28.7	3.49	.6	30.3	4.52	.8
	W	32.3	3.69	.6	33.2	6.03	1.
	E	31.	4.44	.8	30.5	6.20	1.1
	S	25.5	4.52	.8	27.5	4.32	.7
L	F	26.1	3.1	.5	26.7	4.85	.8
	W	27.6	3.72	.6	28.6	4.89	.8
	E	27.5	3.7	.6	28.6	4.15	.7
	S	23.7	3.81	.7	25.2	3.83	.7

TABLE VI.—*Continued.*

RATE: AGE 14.

		Boys, n=41.			Girls, n=33.		
		A	μ	μ_o	A	μ	μ_o
R	F	31.5	3.69	.6	29.5	3.02	.5
	W	33.	3.8	.6	30.3	3.79	.6
	E	32.7	4.63	.7	28.8	2.83	.5
	S	27.2	3.49	.5	26.6	3.17	.5
L	F	[1]27.5	3.69	.6	26.8	2.89	.5
	W	29.	2.61	.4	28.	3.70	.6
	E	28.6	3.62	.6	26.9	3.48	.6
	S	24.3	3.49	.5	23.8	3.34	.6

[1]n=40 in L, F.

RATE: AGE 15.

		Boys, n=32.			Girls, n=31.		
		A	μ	μ_o	A	μ	μ_o
R	F	31.6	4.02	.7	29.1	3.44	.6
	W	34.2	4.46	.8	30.9	4.31	.8
	E	31.5	3.72	.7	29.3	3.84	.7
	S	26.3	3.29	.6	26.	3.89	.7
L	F	28.3	3.46	.6	26.7	3.23	.6
	W	29.5	3.60	.6	28.3	3.97	.7
	E	28.7	3.61	.6	27.6	4.01	.7
	S	24.7	3.58	.6	25.4	4.14	.7

RATE: AGE 16.

		Boys, n=26.			Girls, n=17.		
		A	μ	μ_o	A	μ	μ_o
R	F	33.9	4.92	1.0	31.3	4.66	1.1
	W	35.9	5.16	1.01	30.1	4.93	1.09
	E	32.7	3.90	.8	33.3	4.52	1.2
	S	28.7	3.42	.7	27.9	3.44	.8
L	F	30.7	5.08	1.0	28.6	4.01	1.0
	W	33.1	4.70	.9	29.5	3.87	.9
	E	30.7	2.68	.5	28.2	3.75	.9
	S	26.6	3.52	.7	26.2	3.55	.8

The Degree of Trustworthiness of Results.

I have endeavored to state fully the conditions under which the foregoing tests were made, so that the *a priori* probability of their trustworthiness might be estimated. There are, however, two ways of determining from the results themselves their probable degree of trustworthiness. From whatever known or unknown sources of error the work may have suffered, the net errors are probably within the limits thus ascertained.

1. The mean errors of the means.

Inspection of the tables or charts shows that the limits of mean errors of the means are in all cases absolutely small, and small in comparison with the values of the corresponding means. Further examination shows:

Average of the 160 values of μ_o for ages 6-15,	.57 taps in 5″
Sixty-eight per cent. of these values range from 0 to	.67 " " "
Maximum value of μ_o,	1.1 " " "

Seventy-seven per cent. of the values of μ_o are less than 2% of their corresponding means.

In sum, if an equal number of individuals, corresponding in age and sex to any class for whom means are here given, be tested under the same conditions, the probability is .683 that the resulting mean will not differ from that here given by more than .67 taps in 5″, and the probability is .978 that the resulting mean will not differ from that here given by more than one tap in 5″.

The relatively small number of individuals of 16 upon whom measurements could be obtained renders the means at that age somewhat less reliable:

Average value of μ_o for age 16,	.9 taps in 5″
Maximum value of μ_o,	1.2 " " "
Average $\frac{\mu_o \cdot 100}{A}$	3% " " "

2. An independent means of judging the degree of trustworthiness of the means is furnished by a comparison of the results from boys with those from girls. It cannot be assumed, and is in fact later shown to be untrue, that the rates for boys and for girls of the same age are approximately equal. On the contrary there appear clearly defined differences varying with the age examined. But if, the fact of characteristic differences between the two sexes having been established, it should appear that the two sets of wholly independent means differ from each other within very narrow limits, then it is probable that two sets of independent means obtained from individuals of the same sex would differ from each other within still narrower limits, certainly not wider ones. If the values of (B-G) for the 88 possible comparisons

(11 ages, 8 joints) between corresponding mean rates of boys and girls be determined, the differences in the mean rates of boys and girls is shown to be very small. Of the 88 values of (B-G),

3	differ	by	3 taps	or	over	in	5	seconds.
14	"	"	2 "	"	"	"	"	"
19	"	"	1 "	"	"	"	"	"
52	"	"	less than 1 tap			"	"	"

In 59 of 88 cases, $(B\text{-}G) < (\mu_0 B + \mu_0 G)$[1]

That is, in 67% of the cases the difference between the mean rate for boys and the corresponding rate for girls is within the limits of the mean errors of the means compared.

Mean Variation: It will be noted that the mean individual variation is subject to considerable fluctuation. Examination shows that periods of most rapid acceleration are generally periods of widening individual variation, while periods of greatest retardation or decline are periods of narrowing individual variation. The mean individual variation rarely (seven times out of 184) exceeds one tap per second.

Extreme Limits of Variation of Rate.

The lowest mean rate found is 17.9 taps in five seconds (girls left shoulder, 6), the highest mean rate found is 35.9 taps in five seconds (boys, right wrist, 16). If the corresponding mean variation be taken into account, we have 15.5 and 41.2 as the limits within which nearly all individual cases may be expected to fall. Not all, however. In order to show the fact and the degree of probability of extreme high and low rates, I have tabulated the individual results which show rates of less than 4 and of more than 8 per second.[2]

Representing by A the mean rate of a given age; by $A \pm \mu$ the mean with its individual variation; and by N the limits within which 99% of all individual casès fall, we have:

---

[1] $\mu_0 B$=mean var. of a mean rate of boys. $\mu_0 G$=same for a mean rate of girls.

[2] Very high rates were usually repeated. The best single record was made by a girl, F. W., of 12 in the sixth grade, as follows: R. F., 40; W., 48. (Second trial 47), E., 40; S., 34; L. F., 32; W., 43; E., 40; S., 34.

She looked the type of robust-health. When asked if she played the piano she said, "Only by ear; but I play base ball though," adding a moment later, "I can strike two over an octave on the piano." Another of many interesting individual records is that of A. C., a girl of 13, who has taken lessons upon the violin for two years: R. F., 42; W., 43; E., 40; S., 34; L. F., 42; W., 42; E., 34; S., 26.

The high rates of the joints most involved in playing the violin in connection with the low rate of the left shoulder form an interesting picture of the effects of special practice.

	A	A+μ	N
Upper Limit	35.9	41.2	45 taps in 5″
	A	A—μ	N
Lower Limit	17.9	15.5	12 " " "

Of the 5,944 single measurements (including those from five year old children) we have,

Below a rate of 3 per second,	2 cases.
From 3 to 4 per second,	166 "
" 4 " 8 " "	5,709 "
" 8 " 9 " "	61 "
9 per second or over,	6 " [1]

Variation of Rate with Age.

Inspection of the tables or charts shows for both sexes and for all joints an increase of rate with age. The total amount of increase in the rate of each joint in the ten years from 6 to 16 is shown in the following table. A change in decimal point gives the average yearly increase.

Total increase in rate between ages 6 and 16, in terms of x taps in 5″:

Boys' right—F., 14.4 ; W., 12.9 ; E., 9.2 ; S., 8.9.
Boys' left — F., 12.7 ; W., 13.3 ; E., 10.3 ; S., 8.4.
Girls' right—F., 11.5 ; W., 8.5* ; E., 7.4* ; S., 8.0.
Girls' left—F., 10.6 ; W., 10.6 ; E., 8.5* ; S., 8.3.

*Higher at 13 than at 16.

The amount of increase is not, however, the same each year. Table VII. gives the amount of increase or decrease for each joint in each year period. Numbers less than the average increase are printed in italics. Table VIIa. shows the periods of most obvious acceleration and retardation of growth.[2]

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[1]For the behavior of the different joints in successive years, see p. 66.

[2]This table is given not to show the distribution, but the extreme limits of rates found.

TABLE VII.

SHOWING AMOUNT OF INCREASE OR DECREASE IN THE RATE OF EACH JOINT EACH YEAR FROM 6–16 IN TERMS OF X TAPS IN 5.″

Ages		6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16
Boys' Right.	F	1.5	2.1	1.3	.8	1.8	2.3	–.6	2.8	.1	2.3
	W	.7	2.6	1.5	.7	1.8	1.3	.7	1.5	.4	1.7
	E	.7	1.9	2.1	–.1	1.2	.6	1.1	1.7	–1.2	1.2
	S	.7	1.8	1.8	–1.5	1.5	.9	.5	1.8	.9	2.5
Boys' Left.	F	1.1	1.4	1.0	.9	1.5	2.3	–.2	1.4	.8	2.4
	W	.5	2.0	1.4	.9	1.4	1.0	.7	1.4	.5	3.6
	E	.5	1.4	1.5	.9	1.3	.3	1.2	1.1	.1	2.0
	S	.6	1.4	.7	.4	1.0	.9	1.3	.6	.4	2.1
Girls' Right.	F	.9	1.5	1.8	1.8	1.3	1.1	2.1	–.8	–.4	2.1
	W	1.5	1.2	1.2	3.0	1.9	1.2	1.6	–2.9	.6	–.8
	E	.5	1.2	1.0	2.1	1.1	.8	.9	–1.7	.5	.8
	S	.3	1.7	.8	–.1	2.3	.8	1.8	–.9	–.6	1.9
Girls' Left.	F	1.1	.6	.9	1.7	2.6	.9	.9	.1	–.1	1.9
	W	1.1	1.0	1.4	1.9	2.0	.7	1.6	–.6	.3	1.2
	E	1.8	.1	1.0	1.4	2.2	.0	2.4	–1.7	.7	.6
	S	.9	1.4	.6	.8	2.0	.0	1.6	–1.4	1.6	.8

TABLE VII a.

Every joint shows an increase greater than the average yearly increase for that joint:

In boys, at ages 7-8, 10-11, 15-16. In girls, 10-11.

Seven of the eight joints show accelerated growth :

In girls, 12-13.

Six of the eight joints show accelerated growth :

In boys, 13-14. In girls, 9-10.

Five of the eight joints show accelerated growth:

In boys, 8-9, 11-12. In girls, 6-7, 7-8, 8-9, 15-16.

Five of the eight joints show an increase of rate less than the average yearly increase for that joint, or a decrease:

In boys, 12-13. In girls, 11-12.

Seven of the eight joints show retardation, or decrease:

In boys, 6-7. In girls, 14-15.

Eight joints show retardation, or decrease :

In boys, 9-10, 14-15. In girls, 13-14.

The degree of acceleration or retardation of growth is shown graphically for each joint each year in the rate chart (I.) by the directions of the solid lines connecting the year-

averages. The plus or minus value of the angle which this line makes with the base line is measured by $\frac{\pm\Delta y}{\Delta t}$, Δt being the constant, 25 mm., and $\pm\Delta y$ being the increase or decrease for the year.

It is obvious from the tables and from the charts that there are certain periods when all or nearly all the joints grow at an accelerated rate, and other periods when all or nearly all grow at a retarded rate or even decline in ability; and it is clear what those periods are. Table VII a. The periods of most considerable and most significant decline are for boys from 14 to 15 and for girls from 13 to 14. It will be observed that in each of these cases the period of decline is preceded by a period of acceleration and is followed by a more or less rapid recovery.[1]

Comparison of Right and Left.

Method of Calculation.

The mean differences between the rates of right side joints and of the corresponding left side joints are obtained from the data in two arithmetically independent ways. (a) The mean rate for a given joint may be compared with that of the corresponding joint on the other side; or (b) the mean of the individual differences between corresponding joints may be ascertained. Both processes must give the same result and they furnish a check against error in calculation.

The values of (r-l) have a higher probability than the values of r or of l.[2] This would be expected a priori, if it were assumed that any degree of correlation exists between corresponding right and left joints. That is, in an entirely new set of individuals a variation in the mean of a right side joint would likely be accompanied by a variation in the mean of the corresponding left side joint, not of precisely the same amount but in the same direction.

That the values of (r-l) *are* more trustworthy than those of r or of l appears from the following consideration: On page 157 it was shown that the mean of the values of μ_0 is .56 taps in 5″ and that two thirds of the values of μ_0 are less than .67 taps in 5.″ If the value of (r-l) be found by the second (b) method described above, the mean variation of individual (r-l) values from the mean (r-l) and the mean variation of the mean (r-l) may be found by the same process as that described on page 151. These calculations were made.[3] The values of

[1]For a comparison of boys and girls in this respect see P. 174. For a discussion of the significance of the facts, see P. 200.

[2]r = mean rate of a right side joint; l = mean rate of a left side joint.

[3]See page 166, where an example of this calculation is given; and pages 167, the results for each pair of joints.

μ_{OB}[1] for ages 6 to 15 have an average value of .46 taps in 5″; and two thirds of these values are under .54 taps in 5.″

Mean Values of (r-l).

The mean rate of every right side joint is faster than that of the corresponding left side joint; and in every case the plus value of (r-l) is greater than its mean variation. In forty-seven of the 88 cases (11 ages, 4 joints, 2 sexes), (r-l) is greater than the corresponding mean individual variation. The values of each (r-l) may be found from the rate tables, page 153–156. The average values for each joint are as follows:

TABLE VIII.

	Mean of (r-l) values from 6 to 16.	Mean variation of yearly (r-l) values from mean $\frac{\Sigma v.}{n}$	
Boys' Finger	2.8	.68	
" Wrist	4.	.6	
" Elbow	3.4	.58	
" Shoulder	2.2	.53	All values in terms of X taps in 5.″
Girls' Finger	2.7	.62	
" Wrist	3.4	.8	
" Elbow	2.5	.58	
" Shoulder	1.7	.8	

Limits of Variation of (r-l).

TABLE IX.

2,992 individual values of (r-l) are distributed in the following proportions:

More than	15 taps in 5″	.001	
" "	10 and under, 15 taps in 5″	.012	
" "	5 " " 10 " " "	.132	
" "	0 " " 5 " " "	.642	.787 positive.
At	0	.111	
Below	0 and above—5 " " "	.100	.102 negative.
Under	—5 taps in 5″	.002	

Variations of (r-l) with Age.

1. The mean values of r and of l tend to vary together.

If the yearly increase or decrease in the mean rate of each right side joint be compared with the yearly increase or decrease in the mean rate of the corresponding left side joint, we have in all 80 comparisons (ten year periods, four pairs of

[1] μ_{OB} = mean variation of mean (r-l).

joints, boys and girls). In 91% of these 80 cases the r and l means both show increase or both show decrease. In 85% of the cases the r and l means both show acceleration or both show retardation.

2. The right side joints are subject to greater fluctuation of rate ability than are the left side joints.

Of 68 cases where r and l both show increase, r shows a greater increase than l in 46 cases. Of five cases in which both sides show decrease, r shows a greater decrease than l in four cases. Of the remaining seven cases, r shows a greater plus or minus variation than l in three cases. Of the whole 80 cases, 53 show a greater fluctuation in the right than in the left.

3. Variations in the values of (r-l) with age are dependent of course upon the relative rates of growth in r and l. The rate tables on pages 153–156 and the accompanying chart (Chart II.), exhibit these relations. I find myself only able to say on the whole that the right hand gains faster in certain years, but also loses more in other years, so that at 16 the difference between the two sides is almost the same as at the age of 6.

The total gains of r over l between ages 6 and 16, i. e., (r-l) at 16 minus (r-l) at 6, are as follows:

Boys: F 1.7; W –.4; E –1.1; S .5 taps in 5″ Average .17.
Girls: F .9; W 1.1; E –1.1; S –.3 " " " " .15.

Bilateral Symmetry and Asymmetry of Rate Ability.

It has been shown that the mean rate of right side joints is always greater than that of the corresponding left side joints. It is very desirable to know whether the two sides increase in ability together, and if not, to determine the degree of asymmetry in their development. This does not appear from a comparison of mean rates of right and left side joints in successive years. That widely varying degrees of bilateral correlation might exist in the presence of any given mean rates upon the two sides may be shown by the following illustration:

Let the individuals A, B, C, D and E have the rates 6, 9, 12, 8 and 5 in a right side joint, and the rates 4, 7, 10, 6 and 3 in the corresponding left side joint, it being undetermined which two rates belong to any individual. Assume three distributions of the rates among the individuals as follows:

		R	L	Difference
I	A	6	4	2
	B	9	7	2
	C	12	10	2
	D	8	6	2
	E	5	3	2

Average R=8. Its $\sqrt{\frac{\Sigma v^2}{n}}=\sqrt{6}$

Average L=6. Its $\sqrt{\frac{\Sigma v^2}{n}}=\sqrt{7.4}$

Average D=2. Its $\sqrt{\frac{\Sigma v^2}{n}}=0$

		R	L	Difference
II	A	6	3	3
	B	9	10	-1
	C	12	6	6
	D	8	7	1
	E	5	4	1

Average R=8. $\sqrt{\frac{\Sigma v^2}{n}}=\sqrt{6}$

Average L=6. $\sqrt{\frac{\Sigma v^2}{n}}=\sqrt{7.4}$

Average D=2. $\sqrt{\frac{\Sigma v^2}{n}}=\sqrt{5.7}$

		R	L	Difference
III	A	6	6	0
	B	9	4	5
	C	12	3	9
	D	8	7	1
	E	5	10	-5

Average R=8. $\sqrt{\frac{\Sigma v^2}{n}}=\sqrt{6}$

Average L=6. $\sqrt{\frac{\Sigma v^2}{n}}=\sqrt{7.4}$

Average D=2. $\sqrt{\frac{\Sigma v^2}{n}}=\sqrt{26.4}$

I. is a case of perfect bilateral correlation; II. a case of partial correlation; III. a case of non-correlation.

It is obvious that the value $\sqrt{\frac{\Sigma v^2}{n}}$ obtained from the column of differences between r and l is a measure of the fluctuation of individual (r-l) values from the mean (r-l). In order to determine whether a given value of $\sqrt{\frac{\Sigma v^2}{n}}$ indicates correlation or non-correlation, and what degree of either, it is necessary to determine what the value of $\sqrt{\frac{\Sigma v^2}{n}}$ would be if the relation between right side rates and left side rates *were determined by chance*, i. e., if the r values and l values were placed in separate boxes and paired, by drawing one from each box at a time.

This chance value of $\sqrt{\frac{\Sigma v^2}{n}}$ may be determined as follows :[1]

Let R=mean rate of a right side joint.
$(R+r)$=any individual rate by that joint.
μ_R=mean individual variation=$\sqrt{\frac{\Sigma v^2}{n}}$

[1] I am indebted for this method and development to Dr. Franz Boas, to whom I hereby return hearty thanks.

L=mean rate of corresponding left side joint.
(L+l)=any individual rate by that joint.
μ_L=corresponding mean individual variation.[1]

(1) Then $P_{(R+r)} = \frac{1}{\mu_R \sqrt{2\pi}} \varepsilon - \frac{r^2}{2\mu_R^2}$

and $P_{(L+l)} = \frac{1}{\mu_L \sqrt{2\pi}} \varepsilon - \frac{l^2}{2\mu_L^2}$

are the respective probabilities of any rates (R+r), and (L+l).

If these probabilities are independent of each other, the probability that (R+r) and (L+l) will occur together is:

(2) $P_{(R+r)} P_{(L+l)} = \frac{1}{\mu_R \mu_L 2\pi} \varepsilon - \frac{r^2}{2\mu_R^2} - \frac{l^2}{2\mu_L^2}$

(R+r) — (L+l) = (R—L) + (r—l). Substituting u for (r—l).

(3)
$$P_{R-L+u} = \int_0^\infty \frac{1}{\mu_R \mu_L^2 2\pi} \varepsilon - \frac{r^2}{2\mu_R^2} - \frac{(r-u)^2}{2\mu_L^2}$$
$$= \frac{1}{\sqrt{2\pi}\sqrt{\mu_R^2+\mu_L^2}} \varepsilon - \frac{u^2}{2(\mu_R^2+\mu_L^2)}$$

It thus appears that if the individual rate (R+r) and the individual rate (L+l) are independent of each other, the mean individual variation in the values of (R+r)—(L+l) will be $\sqrt{\mu_R^2+\mu_L^2}$ that is, the square root of the sum of the squares of the mean individual variations of (R+r) and (L+l) respectively. The Table XI., page 167, and the Chart III., give the values of μ_0 and of $\sqrt{\mu_R^2+\mu_L^2}$ and of $\frac{\mu_0.100}{\sqrt{\mu_R^2+\mu_L^2}}$ for each pair of joints at each age from 6 to 16.

The last quantity shows the relation in per cent between the chance value and the actual degree of the bilateral asymmetry. The Table X., page 166, gives an example of the method of determining μ_B (for boys' finger, 6).

Table showing the method of calculating the mean variation of individual values of (r—l), about the average value of (r—l) for boy's finger, 6. Unit=1 tap in 5 seconds.

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[1] For the purposes of this calculation R is used instead of r for the mean rate of a right side joint, and likewise L for l.

TABLE X.

Differences between r and l in individual cases=d.	No. of cases of each difference found=n.	dn.	Residuals =v.	v^2	nv^2
-2.	2	-4.	3.3	10.80	21.78
-1.	2	-2.	2.3	5.29	10.58
0.	4	0.	1.3	1.69	6.76
1.	5	5.	.3	.09	.45
2.	8	16.	.7	.49	3.92
3.	2	6.	1.7	2.89	5.78
4.	2	8.	2.7	7.29	14.58
5.	1	5.	3.7	13.69	13.69
	n=26	34.			$\Sigma v^2 = 77.54$

$$\frac{34}{26}=1.3+=\text{Av. } (r-l).$$

$$\sqrt{\frac{77.54}{26}}=1.73-=\mu\ (r-l).$$

$$\frac{1.73}{\sqrt{26}}=.3+=\mu_o\ (r-l).$$

Table XI.

Rate: Bilateral Symmetry.

Age		Boys. [1] $\sqrt{\mu_B^2+\mu_L^2}$	Boys. [2] $\mu_B^{(2)}$	Boys. [3] $\frac{\mu_B .100}{\sqrt{\mu_B^2+\mu_L^2}}$ %	Girls. $\sqrt{\mu_B^2+\mu_L^2}$	Girls. $\mu_B^{(2)}$	Girls. $\frac{\mu_B .100}{\sqrt{\mu_B^2+\mu_L^2}}$ %
6	F	2.41	1.73	71.8	3.75	2.5	45.3
	W	3.55	2.43	68.4	3.47	2.25	64.8
	E	3.13	2.34	74.7	3.01	1.78	59.1
	S	3.62	2.58	71.2	3.61	2.43	67.3
7	F	3.5	2.57	73.4	4.06	3.35	82.5
	W	3.9	2.71	69.4	3.68	2.44	66.3
	E	4.83	2.54	52.5	3.61	1.78	49.3
	S	3.54	2.34	66.1	3.82	2.27	59.4
8	F	3.28	2.12	64.3	3.82	2.18	57.
	W	4.03	2.53	62.7	3.82	2.39	62.5
	E	3.68	2.40	65.2	3.55	1.84	51.8
	S	3.42	2.41	70.4	4.11	2.01	48.9
9	F	5.46	2.92	53.4	4.04	2.69	66.5
	W	5.17	3.36	64.9	4.39	2.55	58
	E	5.09	3.18	62.4	4.68	2.95	63.
	S	5.09	2.80	55.	4.83	2.55	52.7
10	F	3.86	1.62	41.9	4.28	2.99	69.8
	W	4.96	3.06	61.7	4.41	3.20	72.5
	E	4.5	2.76	61.3	3.91	2.78	71.
	S	3.89	2.39	61.4	3.82	2.19	57.3
11	F	4.44	2.59	58.3	4.88	2.84	58.1
	W	5.9	3.56	60.2	5.87	3.54	60.3
	E	4.81	2.92	60.7	4.95	3.26	65.8
	S	3.89	3.09	79.4	4.74	2.63	55.4
12	F	6.6	4.43	67.1	5.25	2.68	51.
	W	6.38	3.62	56.7	7.	3.08	44.
	E	5.52	3.09	55.9	6.72	2.64	30.3
	S	4.88	2.78	56.9	5.61	2.77	49.3
13	F	4.67	3.49	74.7	6.58	3.14	47.7
	W	5.16	3.32	64.3	7.75	3.46	44.6
	E	5.75	3.23	57.9	7.27	3.52	48.4
	S	5.89	2.53	42.9	5.51	3.01	56.4
14	F	5.23	3.33	63.6	4.17	3.33	58.7
	W	4.64	2.89	62.2	5.3	2.89	57.8
	E	5.84	4.07	69.6	4.48	3.50	78.1
	S	4.95	3.21	65.	4.59	3.40	74.2
15	F	5.31	3.94	74.1	4.67	2.91	62.3
	W	5.76	3.65	63.1	5.87	3.34	56.8
	E	5.16	2.78	55.8	5.51	2.42	43.9
	S	4.88	2.94	60.2	5.59	2.41	43.1
16	F	7.08	4.16	58.7	6.17	2.61	42.3
	W	7.01	4.32	61.6	6.26	2.13	34.
	E	4.86	2.94	60.4	5.83	3.66	62.7
	S	4.88	2.87	58.8	4.88	3.04	62.2

[1] This column is the *solid upper* line in bilateral charts. (III.)
[2] This column is the *dotted lower* line in bilateral charts.
[3] This column shows per cent. of actual bilateral asymmetry to its chance value.

The fact of a certain degree of bilateral asymmetry and of a certain degree of bilateral symmetry, and the degree of each, are thus shown for each pair of joints at each age.

Bilateral Symmetry and Asymmetry of Development.

If it should appear that μ_B changes from year to year in the same direction and in an approximately corresponding degree with $\sqrt{\mu_R^2+\mu_L^2}$ then it would be inferred that the causes which determine the fluctuations of individual variation determine also the fluctuations of bilateral asymmetry; otherwise stated, that corresponding right and left side joints in most individuals do not grow together, do not have corresponding acceleration and retardation of growth together. Tendency of the curve μ_B to move parallel with the curves $\sqrt{\mu_R^2+\mu_L^2}$ is so far proof of asymmetrical growth.

On the other hand, if it should appear that μ_B altogether refuses to fluctuate with $\sqrt{\mu_R^2+\mu_L^2}$ then it would be inferred that the causes which bring about fluctuations of individual variations do not affect the degree of bilateral asymmetry; otherwise stated, that corresponding right and left side joints in most individuals grow together; have corresponding acceleration and retardation of growth together, through whatever periods of individual variation. Tendency of the curve μ_B to move independently in direction of the curve $\sqrt{\mu_R^2+\mu_L^2}$ is so far proof of symmetrical growth.

If we determine the amount of yearly increase or decrease in the values of μ_B and of $\sqrt{\mu_R^2+\mu_L^2}$ for each joint, we have in each case 80 results, 40 for boys and 40 for girls. A comparison of the 80 plus or minus increments of μ_B with the 80 plus or minus increments of $\sqrt{\mu_R^2+\mu_L^2}$ gives the following results :

I. μ_B and $\sqrt{\mu_R^2+\mu_L^2}$ tend to vary in the same direction oftener than would be accounted for by chance. In 35 out of 80 comparisons, both increase ; in 15 out of 80 comparisons, both decrease ; i. e., in 50 out of 80 comparisons, both change in the same direction. There is, therefore, so far, bilateral asymmetry of development.

The probability from the totals is 62.5 per cent that the degree of bilateral asymmetry will be changed to some extent in the same direction as the given function of the individual variations. For finger, wrist and elbow, the probability is greater, viz.: 70%, or 20% more than an even chance.

2. Besides the 30 cases out of the total 80 in which μ_B and $\sqrt{\mu_R+\mu_L^2}$ do not vary in the same direction, there are 38 cases in which the latter varies more than the former. There

is, therefore, so far, symmetry of development of the two sides.

The probability is 72.5% that the given function of the individual variation will fluctuate more than the bilateral asymmetry; and the probability is 85% that the mean variation will fluctuate more than the bilateral asymmetry or will change in the opposite direction. The probability is 15%, or 35% less than an even chance, that in any given case the bilateral asymmetry will vary in the same direction and in a greater degree than the given function of the mean variation.

The following table gives the mean values of μ_B and of $\sqrt{\mu_R^2+\mu_L^2}$ for each joint of boys and of girls, together with the corresponding $\left(\frac{\Sigma v}{n}\right)$ fluctuation of yearly values from the mean. In each case the fluctuation is shown to be much greater for $\sqrt{\mu_R^2+\mu_L^2}$ than for μ_B.

TABLE XII.

		Finger	$\frac{\Sigma v}{n}$	Wrist	$\frac{\Sigma v}{n}$	Elbow	$\frac{\Sigma v}{n}$	Shoulder	$\frac{\Sigma v}{n}$
$\sqrt{\mu_R^2+\mu_L^2}$	Boys	4.53	1.13	5.13	.85	4.74	53.	4.44	.70
	Girls	4.60	.73	5.25	1.15	4.86	1.08	4.64	.59
μ_B	Boys	2.95	.79	3.22	.45	3.02	.36	2.72	.25
	Girls	2.86	.27	2.93	.45	2.79	.54	2.52	.32

The fact and the degree of each tendency are shown in the graphical representation of each pair of joints by the relative directions of the lines connecting successive values of μ_B and of $\sqrt{\mu_R^2+\mu_L^2}$. The tendency of the two curves to run parallel and the greater fluctuation of the upper curve are both evident. It is, therefore, to be concluded that there is partial, and only partial, bilateral asymmetry in the development of the rate of voluntary movement. Corresponding joints do not have exactly corresponding growth, but the correspondence is considerably closer than would be accounted for by chance.

Comparison of the Joints.

The order of the joints as regards rate is not the same at all ages. The following table shows the order at each age:

TABLE XIII.

Order		1	2	3	4	Order		1	2	3	4
6	E	4	0	0	0	7	E	4	0	0	0
	W	0	4	0	0		W	0	4	0	0
	S	0	0	3	1		F	0	0	4	0
	F	0	0	1	3		S	0	0	0	4
8[1]	E	3	0	0	0	9	E	3	1	0	0
	W	0	3	0	0		W	1	3	0	0
	F	0	0	3	1		F	0	0	3	1
	S	0	0	1	3		S	0	0	1	3
10	W	4	0	0	0	11	W	3	1	0	0
	E	0	4	0	0		E	1	3	0	0
	F	0	0	4	0		F	0	0	4	0
	S	0	0	0	4		S	0	0	0	4
12[2]	W	4	0	0	0	13	W	3	1	0	0
	E	0	3	0	0		E	1	3	0	0
	F	0	0	3	0		F	0	0	4	0
	S	0	0	0	4		S	0	0	0	4
14	W	4	0	0	0	15	W	4	0	0	0
	E	0	3	1	0		E	0	3	1	0
	F	0	1	3	0		F	0	1	3	0
	S	0	0	0	4		S	0	0	0	4
16[3]	W	4	0	0	0						
	F	0	3	0	0						
	E	0	0	3	0						
	S	0	0	0	4						

[1]E=W1. [2]E=F. [3]E=F.

The figures show the number of times, out of a possible 4, that the given joint stands in the order indicated. Thus at the age of 6, the mean rate of the elbow is highest in four cases,— boys R and L, and girls R and L.

TABLE XIV.

Table showing the number of times, out of a possible 44, each joint is found in each order as regards rate.

	Highest	Second	Third	Lowest	
Wrist	27	16	0	0	= 43
Elbow	16	20	5	0	= 41
Finger	0	5	32	5	= 42
Shoulder	0	0	5	39	= 44

Once E=W. Twice E=F.

The following table shows the amount by which elbow, wrist and finger severally exceed the shoulder at each age:

TABLE XV.

	Boys.				Girls.		
	Years	E–S	W–S	F–S	E–S	W–S	F–S
Right	6	3.7	3.4	–.3	2.8	1.7	–.1
	7	3.7	3.2	.5	3.0	2.9	.5
	8	3.8	3.8	.8	2.5	2.4	.3
	9	4.1	3.7	.3	2.7	3.2	1.3
	10	6.5	5.9	2.6	4.9	5.9	3.2
	11	5.6	6.4	2.9	3.7	5.5	2.2
	12	4.9	6.6	4.3	3.7	5.9	2.5
	13	5.6	6.8	3.2	3.7	5.7	2.8
	14	5.5	5.8	4.3	3.0	3.7	2.9
	15	4.9	7.9	5.3	2.2	4.9	3.1
	16	4.0	7.3	5.3	3.1	5.4	3.4
Left	6	2.2	1.5	–.2	1.8	1.0	.1
	7	2.1	1.4	.3	2.7	1.2	.3
	8	2.1	2.0	.3	1.4	.8	–.5
	9	2.9	2.7	.6	1.8	1.8	–.2
	10	4.2	4.2	1.9	2.4	2.5	.7
	11	4.5	4.4	2.4	2.6	2.7	1.3
	12	3.9	4.5	3.9	2.6	3.4	2.2
	13	3.8	3.9	2.4	3.4	3.4	1.5
	14	4.3	4.7	3.2	3.1	4.2	3.0
	15	4.0	5.1	3.8	2.2	2.8	1.3
	16	4.1	6.4	4.1	2.0	3.3	2.4

These results show that the shoulder grows most slowly, the elbow slightly faster, the wrist and finger very much more

rapidly. At 6, the finger joint is slowest, the elbow fastest; at 16, the finger has passed the elbow.[1]

Longitudinal Asymmetry.

It is possible, by the method employed in determining the fact and degree of bilateral asymmetry, to determine whether there is any degree, and if so, what degree, of longitudinal asymmetry. The results for the right side in boys of 6, 9, 12 and 15 were treated in this manner, the remaining material being reserved for future treatment. The following table shows a comparison of the values of $\mu_{\text{Long.}}$ with the values of $\sqrt{\mu_{J1}^2+\mu_{J2}^2}$ for the ages named, finger and wrist, wrist and elbow, elbow and shoulder; finger and shoulder being so compared.

μ_J = mean variation of one of the joints compared.
$\mu_{\text{Long.}}$ = mean variation of individual values of (J_1-J_2) from their mean.

Table XVI.

Table Showing Longitudinal Asymmetry.

		I	II	III
Joints Compared	Ages	$\sqrt{\mu_{J1}^2+\mu_{J2}^2}$	Long. Asymmetry $\mu_{\text{Long.}}$	$\frac{\text{II. } 100}{\text{I.}}$ = % of Asymmetry
Finger and Wrist	6	3.25	2.15	.66
	9	5.43	2.94	.49
	12	7.61	4.05	.53
	15	6.	3.89	.65
Wrist and Elbow	6	3.08	2.72	.88
	9	4.97	2.52	.50
	12	6.69	3.50	.52
	15	5.81	4.02	.69
Elbow and Shoulder	6	3.16	3.25	1.02
	9	5.07	2.54	.50
	12	5.29	3.52	.66
	15	4.97	3.49	.70
Finger and Shoulder	6	3.33	3.15	.94
	9	5.54	4.21	.76
	12	6.34	4.04	.63
	15	5.19	4.36	.84

[1] For discussion, see page 201.

The fact of partial and only partial asymmetry of development, is thus shown to hold longitudinally as well as bilaterally. It will be observed that the degree of asymmetry approaches most nearly its chance value at age 6, and that in one instance at that age it is slightly in excess of its chance value. As in the bilateral comparisons, however, the absolute degree of asymmetry does not change much with age. The greatest asymmetry, absolute and relative, appears between finger and shoulder; the greatest correlation, between finger and wrist.

Boys and Girls.

It was shown on page 50 that the differences between boys and girls are slight. Within the narrow limits there indicated, however, there is a slight superiority of boys over girls. Of the 29 cases in which the difference between boys and girls is greater than $(\mu_{OB}+\mu_{OG})$,[1] 24 are in favor of the boys and 5 in favor of the girls. Of the remaining 59 cases, 33 are in favor of boys, 19 in favor of girls and 7 are the same in both. The superiority of the boys over the girls increases slightly from the age of 6 to the age of 9; and more decidedly from 14 to 16. They are nearest together at 10, 11 and 12. At 13 the girls are superior to the boys for each of the eight joints tested. It has been pointed out elsewhere that the period from 12 to 13 is a period of retardation of rate in boys and acceleration in girls. (Page 160, Table VIIa.)

The superiority of the boys' right side over the girls' right side is slightly greater than the superiority of the boys' left over the girls' left. On the right side, 16 out of 44 cases show $(B—G) > (\mu_{OB}+\mu_{OG})$. Upon the left side there are eight such cases out of 44.

From this fact it comes that there is a slightly greater difference between the right and left sides in boys than in girls. In 33 out of 44 cases [(r-l) boys compared with (r-l) girls] the difference between the right and left is greater for boys than for girls. For each joint the average difference between r and l is greater for boys than for girls. See page 162, Table VIII.[2]

Further light is thrown upon these relations by a study of the increase of rate in boys and girls. If the amount of in-

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[1] μ_{OB} = the mean variation of a mean rate made by boys.
μ_{OG} = " " " " " " " " " girls.

[2] The value of (r-l) boys — (r-l) girls is small, as follows:
2 taps or over in 5 seconds, 2 cases.
Between 1 and 2 taps in 5 seconds, 15 cases.
Less than 1 tap in 5 seconds, 27 cases.

crease in rate for each year be found for each joint tested, the following facts appear:

On the right side the amount of yearly increase of rate is greater for boys than for girls in 24 out of 40 cases. On the left side the boys' rate increases more than that of girls in 20 out of 40 cases. This indicates that on the whole, the boys' right side improves slightly faster than the girls' right side, while the boys' left side improves no faster, possibly more slowly, than the girls' left side.

Bilateral Asymmetry in Boys and Girls.

Above it has been shown that the absolute difference between right and left is greater for boys than for girls, due to the more rapid development of the right side in boys. A study of the mean variation about the average (r–l) shows that there is a closer bilateral correlation in girls than in boys. If we represent by μ_B and μ_G the values of the mean variations about the average (r–l) values for each joint tested, of boys and girls respectively, a table of (μ_B—μ_G) values shows the following results:

1. The value of (μ_B—μ_G) is small, as follows:

In 2 cases out of 44, 2 taps or more in 5 seconds.
" 12 " " " " 1 " " " " " "
" 30 " " " " less than 1 tap in " "
" 31 " " " " the value of (μ_B—μ_G) is less than the sum of the mean errors of the mean (r–l) values concerned.

2. In 12 cases out of 44 (μ_B—μ_G) $>$ ($\mu_{oB}+\mu_{oG}$) and is plus, i. e., the asymmetry is greater for boys than for girls.

In 1 case out of 44 (μ_B—μ_G) $>$ ($\mu_{oB}+\mu_{oG}$) and is minus i. e., the asymmetry is greater for girls than for boys.

In 19 of the 31 cases in which (μ_B—μ_G) $<$ ($\mu_{oB}+\mu_{oG}$), the value of (μ_B—μ_G) is plus. In 10 cases this value is minus. In 2 cases it is 0. In the case of every joint, the average bilateral asymmetry is greater for boys than for girls.

This greater bilateral asymmetry in boys is affected by the varying rapidities of growth in the two sexes. For example, from 9 to 10 and from 12 to 13 are clearly marked periods of retarded growth of rate for boys. In these years, the difference in symmetry between boys and girls is reduced practically to zero. In the years from 7 to 9, or from 15 to 16, on the contrary, especially in the latter period, the greater bilateral asymmetry of boys is clear.

It was pointed out (Page 161) that there is a decline of rate in girls from 13 to 14, and in boys from 14 to 15, that these periods are preceded by a year of accelerated growth, and are followed by more or less rapid recovery. It is significant

that the decline and the antecedent acceleration are more extreme in girls, and that the recovery is slower. In proof:

A comparison of the rates of girls at 13 with the rates of girls at 16, shows that the former almost reach and in three cases surpass the latter.

Fifteen of the twenty-five individual rates of 8 per second or over, made by girls, were made by girls of 13.

Although, as shown elsewhere, the rate of girls is generally slightly less than that of boys,—at the age of 13, every joint shows a higher average in girls than in boys; and in the case of four joints, the girlsof 13 are faster than the boys of 14.

The decline is greater in the case of girls.

Comparison of the retardation of rate in boys from 14 to 15 with that in girls from 13 to 14, shows the latter to be greater in the case of seven of the eight joints. The same facts appear graphically in the rate charts.

The girls recover more slowly.

Comparison of the retardation of rate in boys from 14 to 15 with that in girls from 13 to 14, shows the latter to be greater in the case of seven of the eight joints. The same facts appear graphically in the rate charts.

Comparison of the increments of rate in boys from 15 to 16 with those in girls from 14 to 15, shows the former to be decidedly greater in the case of every joint; and in the case of seven of the eight joints, the increment of rate in boys from 15 to 16 is greater than that in girls from 14 to 16.

Note on Results from Left-handed Children.

The small number of left-handed subjects at any one age prevents much profitable comparison of these records with those from right-handed subjects. In 11 out of 80 (10 yrs., 4 joints, 2 sexes) cases (14%), the mean rate of right-hand joints is greater in left-handed than in right-handed subjects; in 55 out of 80 cases (69%), the left-hand joints of left-handed subjects are faster than the corresponding joints of right-handed subjects; in 66 out of 160 cases (41.2%), the mean rate of joints in left-handed subjects is faster than that of the corresponding joints in right-handed subjects. These percentages are only to be taken as rough approximations.

The fact that values of (r-l) do not fluctuate so much at different ages as to make them incomparable, has caused me to calculate the mean (r-l) for each joint of the 26 boys and of the 20 girls irrespective of age. The results (Table XVII.) show that the average difference between r and l is very small compared with the difference in right-handed subjects, and that notwithstanding the heterogeneity of age the bilateral asymmetry is generally smaller than in right-handed subjects.

XVII.

Table showing mean values of (r-l) in left-handed subjects and degree of bilateral asymmetry.

	Av. (r-l)	$\frac{\Sigma v}{n}$		Av. (r-l)	$\frac{\Sigma v}{n}$
Boys F	1.2	3.3	Girls	—.2	2.4
W	—.1	2.7		.1	3.
E	—.8	2.1		.8	3.1
S	—.2	2.1		—.2	.95

Review of Facts on Rate of Voluntary Movement.

1. The maximum rate of rhythmically repeated voluntary movement is subject to changes in a given individual which are usually slight and gradual. (P. 142.)
2. These changes are sufficient in amount and in constancy to indicate, surely, local and general subjective conditions, as excitement, general and local fatigue, local cold, and the improvement with age. (P. 144 *et seq.*)
3. The change of rate with extreme fatigue is large in comparison with the mean rate of improvement with age. (P. 148.)
4. The amplitude of movement may be changed within wide limits without affecting the rate. (P. 150.)
5. The mean rate of growth of rate between ages 6 and 16 ranges from .15 to .3 taps per second in various joints. (P. 159.)
6. The rate of growth of rate ability is not uniform. Well marked periods of accelerated and of retarded growth appear. (P. 160.)
7. The mean rate of a right side joint, for a group of right-handed subjects, is always higher than that of the corresponding left side joint. The probability that the right will exceed the left in any case chosen at random is about 80%. (P. 161 *et seq.*)
8. The mean rates of corresponding right and left side joints both increase or both decrease in about 90% of cases.
9. Right side joints are subject to slightly greater plus and minus fluctuations of rate ability than are left side joints. (P. 162, 163.)
10. Right side joints gain little if any in rate ability, more than do left side joints. (P. 163.)

11. There is partial and only partial asymmetry of development, bilateral and longitudinal. (P. 163–169, 172.)

12. The hand outgrows the arm between the ages here examined. (P. 170 *et seq.*)

13. The mean rate of boys slightly exceeds that of girls at all ages, except where retardation of growth in boys coincides with acceleration of growth in girls. (P. 173.)

14. There is less bilateral asymmetry of development in the rate ability of boys than in that of girls. (P. 174.)

15. The left-handed persons examined show decidedly less mean difference between right and left and less bilateral asymmetry than do right-handed persons. (P. 175.)

PRECISION OF VOLUNTARY MOVEMENT AS REGARDS FORCE AND DIRECTION.

I.

There is no lack of sufficiently delicate qualitative tests of precision of movement. Personal carriage, speech, games, industrial occupations, scientific technique, fine arts,—in short, all forms of active life afford a multitude of such tests, by means of which the degree of muscular control or lack of it is more or less accurately estimated.

For the clinical determination of precision of movement, besides taking notice of visible irregularities of muscular control and of irregularities shown in any of the subject's ordinary work or play, the following special devices have been used. The patient tries:

1. To draw a straight line ([13]).
2. To write his name or other words ([14]), ([15]).
3. To touch suddenly a specified spot with the point of a pencil ([16]).
4. To hold a reed attached to the finger still, in position to write upon, ([13]) or to cast a shadow upon, ([17]) the revolving drum.
5. To apply constant pressure to some form of dynamograph ([18]), ([19]), ([20]).

All these devices test the control of amount of force exerted, the dynamograph doubtless best. All except the dynamograph test also particularly the control of the direction in which force is exerted. All give or may furnish material for a graphic record of results; and it is not impossible to work out from any of them, with sufficient labor, a numerical result. It is doubtful whether in practice any one seeks to get a numerical result from any of these devices, except the third, and in that case "the result is hardly worth the trouble." (Gowers I. 5.)

II.

The idea has presented itself that precision of movement as dependent upon control of the amount and direction of force may be accurately and conveniently measured, giving a numerical and if desired a graphic result, by a variety of devices the essential point of which is as follows: To one pole of a battery is attached an apparatus which presents a series of spaces, graded in size as finely as desired, and bounded by the conducting medium; to the opposite pole is attached some appropriate form and size of stylus. Or, the stylus may vary in size, the open space in the other electrode being of some appropriate form and size. The task in either case is to determine within what limits of precision either or both of the electrodes may be moved or held still without making contact. The numerical result is read from the instrument. A graphic result can alway be readily constructed from the numerical, and in some forms of apparatus to be described, may be made by the subject.

III.

Five forms of apparatus were made upon this principle, adapted to test various muscles and movements. In the experiments here reported, two of these forms were used. The first of these, Fig. 2, is essentially a device for measuring the precision shown in drawing a straight line. Upon a smooth and hard surface (A) (e. g., glass) were fastened two strips of platinum-foil (B) so that they formed an acute angle 2°-2½°

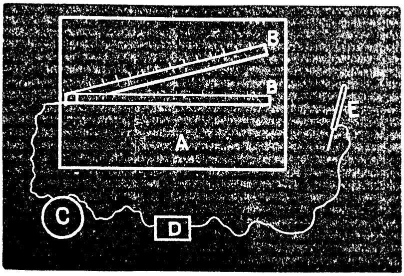

FIG. 2.

A—Plate Glass. *B*—Strips of foil. *C*—Battery. *D*—Sounder. *E*—Stylus.

with each other. The platinum was connected with one pole of a 1 to 4 cell battery (C); to the other pole was attached by flexible wire an ordinary steel pen or needle E. Required to draw a straight line between the arms of the compass as near

as possible to their intersection without making contact.[1] The distance between the arms at the point of contact (minus the thickness of the stylus) is, in general, a measure of deviation from the straight line at that point. The angle at which the arms of the instrument are set is not essential, since chords of every absolute length may be found, at some radius, in every angle; but the angle may be varied for various subsidiary purposes. A little calculation will determine for a given angle, the chords corresponding to each unit of length. Or since radius and chord are functions of each other the direct readings give at once the relative accuracy.

IV.

Preliminary Test of Precision.

In Writing Movement.

A number of conditions aside from the subjective condition of the person experimented upon, appear from prefatory trials to affect the accuracy of the result. (1) The position of the instrument relative to the body, (2) the muscles employed, (3) the support of the muscles employed, (4) the distance moved, affecting variously readjustments of the muscles while in motion, and (5) the rate of motion—all appear to affect the result. In order to make a beginning, even at the determination of these variables, it is necessary to prescribe conditions in at least four of the five. In the prefatory set of experiments with apparatus No. 1, the following conditions have been prescribed: The subject is seated before the table on which the apparatus rests; the forearm and hand are supported by the table; the instrument lies at an angle of about 50° to the right of a perpendicular to the frontal plane, now with the apex of the angle away from the subject and now with the apex of the angle towards him; the subject begins the writing movement 30 mm. from the zero point and moves continuously at any rate he pleases; the angle between the arms of instrument was in the experiments with adults 2°, in the experiment with school children 2½°.

It is believed that the rates, instinctively chosen by the subject, may in the outset be taken in preference to any prescribed rate.[2]

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[1] The zero point is that point at which the stylus just makes contact with both arms of the compass.

[2] See Camerer's conclusion that the natural rate of movement is not a constant, but a gradually accelerated one. P. 138.

Method of Treating Results.

If a be the angle between the arms of the instrument, and l the distance of any point along the scale from the zero point, then half the distance between the arms of the instrument at any point is l sin. $\frac{1}{2}$ a. If t equal the number of trials at the point l, and h equal the number of hits, then $\frac{h\,100}{t}$ is the empirically determined probability in per cent. of a deviation, $l\ sin.\ \frac{1}{2}\ a$.

If we assume $P_{l\ \sin.\ 1\text{-}2\ a} = \frac{2}{\sqrt{\pi}} \int_0^{h\ l\ \sin.\ 1\text{-}2\ a} \varepsilon^{-t^2}\, dt$, the value of $h\ l$ $sin.\ \frac{1}{2}\ a$ corresponding to the ascertained $P_{l\ \sin.\ \frac{1}{2}\ a}$ can be obtained from the table of values of the Probability Integral

$$\frac{2}{\sqrt{\pi}} \int_0^t \varepsilon^{-t^2}\ dt.$$

for argument t. The value of l and of $sin.\ \frac{1}{2}\ a$ are known and h can be obtained from $h = \frac{t}{l\ \sin.\ 1\text{-}2\ a}$.

The value of h, the measure of precision, may be determined in this way for as many different points along the scale as desired. In this work, the determination was made for every millimeter of the scale where there were trials and touches. For points at which no touches were made, of course, no percentage of touches to trials could be obtained.

The degree of precision was thus determined for each set into which the results obtained were classified.

It is not assumed by the foregoing calculation that the value of h is the same for different parts of the scale. The contrary is found to be the fact. This is brought out more clearly by taking the weighted mean of the values of h for each millimeter from 1 to 5, then of the values of h from 6 to 10, and so on in groups of 5 throughout the scale. By weighted means in this case it is meant that each value of h is multiplied by the number of trials made at that point; and that the sum of these products for the several points in the group is divided by the sum of the trials made at the several points in the group. These weighted means represent approximately the average precision of the class for that part of the scale. The values of h thus found are of course abstract numbers, and are significant only in comparison with each other. It seems desirable to know within what limits, in terms of ordinary standards of length, the deviations from a straight line fall. To find within what limits a certain per cent. of cases, say 68.3%, is likely to fall at the point for which the precision is h :

In general,

$$(h^1 x^1) : (h^1 x) : : x^1 : x$$

Where $(h^1 x^1)$=value of t from the Probability Integral table,

x^1=the known value of l sin. $\frac{1}{2}$ a

and $h^1 x=.683$.

$$\therefore \quad x = \frac{.683.\ l\ \text{sin.}\ 1\text{-}2\ a}{h^1\ l\ \text{sin.}\ 1\text{-}2\ a}.$$

Since all the quantities on the right are known, the value of x is obtained by carrying out the indicated operations. This determination was made for the weighted mean of the values of h, for each 5 millimeters of the scale, in the case of each set of results obtained. The tables give in fractions of a millimeter twice the distances within which 68.3% of all deviations from the central line occur, and the weight or number of trials which entered into the determination of each.[1]

The object of this very laborious procedure was to ascertain and take account of the behavior of the pen point in every millimeter of its course and so to increase many fold the information to be obtained from each trial. For example, W. B. made 810 attempts to carry the pen point from 30 mm. to 0 mm. without touching. If the record of these attempts gave information only in respect to one point, namely, the point of touching, the sum of the weights of our information from the experiments could be only 810. But since by the foregoing method it is possible to take account of the average behavior of the pen point at nearly every millimeter of the

[1] Details of the calculation:

Column I. Represented each mm. along the scale from 0-30 mm.
II. The number of touches recorded at each mm.
III. The number of trials made at each mm.
IV. The per cent. of touches to trials at each mm.
V. The per cent. of successes to trials at each mm.
VI. The value of (*h l sin.* $\frac{1}{2}$ *a*) corresponding to the per cent. in V., obtained from the integral table.
VII. The values of (*h sin.* $\frac{1}{2}$ *a*) obtained by dividing by the *l* from column I. Since (*sin.* $\frac{1}{2}$ *a*) is constant these numbers are a measure of precision.
VIII. The products of the numbers in VII., by the corresponding numbers in III.,—i. e., precisions multiplied by their respective weights.
IX. The sums of the numbers in VIII., in groups of five.
X. The quotients of the numbers in IX., by the sums of the corresponding numbers from III. That is, x gives the weighted values of (*h sin.* $\frac{1}{2}$ *a*) for each 5 mm. of the scale.
XI. From each of these, by the method described, page 83, the limits within which 68.3% of all deviations occur were determined. These numbers are given in the tables in connection with their respective weights obtained from column III.

scale, the numerical weight of information about the behavior of the pen in W. B.'s hand is 10,712.[1]

Eight (University) adults were tested in the manner described. Table XVIII. gives the number of trials made by each, the mean distances from the 0 point reached by each and the corresponding individual variations.

Table XIX. gives the results by the method explained page and shows accordingly the breadth of space in fractions of a millimeter within which 68.3% of all deviations fall. The numbers given are twice the deviation in one direction. The number before the colon is in each case the weight of the mean following the colon; thus 465 is the weight of the result .12 mm.

Table XVIII.

Experiments on Precision, Writing Movement.

Persons	No. of Trials	Downward Movement		No. of Trials	Upward Movement	
		Av.	M. V.		Av.	M. V.
J. L.	50	9.6	2.7	50	11.1	3.6
J. A. B.	50	8.7	3.4	50	9.6	2.8
E. C. S.	50	8.2	3.1	50	6.	2.
F. B. D.	75	5.1	2.9	75	5.3	2.7
W. B.	100	5.	2.7	100	8.9	3.2
A. F.	50	4.7	2.1	50	5.3	1.9
T. L. B.	50	6.1	2.7	50	5.3	1.6
L. B.	75	3.9	1.9	75	4.2	1.6

Total number of trials, 1000.

[1] I again heartily acknowledge my indebtedness to Dr. Franz Boas for valuable advice, and at the same time must free him from all responsibility for the method which I have adopted.

TABLE XIX.

Part of Scale		I 1—5	II 6—10	III 11—15	IV 16—20	V 21—25	VI 26—30
		W't mm	W't mm	W't mm	W't mm	W't mm	W't mm
Subject L. B.	R Down	465 : .12	931 : .11	194 : .22			
	R Up	411 : .16	1057 : .12	443 : .16			
Subject T. L. B.	R Down	58 : .19	188 : .14	157 : .19			
	R Up	58 : .18	223 : .15				
Subject A. F.	R Down	96 : .12	217 : .14	50 : .17			
	R Up	60 : .16	201 : .15	144 : .19			
Subject F. B. D.	R Down	146 : .12	317 : .13	141 : .16	72 : .27	74 : .38	
	R Up	124 : .11	306 : .14	286 : .19		74 : .34	
Subject J. A. B.	R Down	24 : .22	156 : .19	192 : .22	56 : .29	59 : .41	
	R Up	6 : .39	141 : .22	143 : .21	159 : .26	116 : .31	
Subject E. C. S.	R Down	21 : .33	161 : .18	131 : .20	95 : .24	49 : .33	50 : .39
	R Up	65 : .16	222 : .14	150 : .26			
Subject J. L.	R Down		115 : .24	157 : .21	132 : .27		
	R Up		73 : .27	172 : .26	46 : .30	144 : .32	50 : .38
Subject W. B.	R Down	290 : .17	1470 : .19	1969 : .17	1626 : .19		
	R Up	244 : .16	1247 : .20	1872 : .20	1994 : .21		

1. Under the conditions named, the mean deviation varies in the eight individuals from about $\frac{.12}{2}^{mm}$ to about $\frac{.38}{2}^{mm}$ (×).

(×) That is, the deviations in one direction are one-half the numbers given in the table.

2. The mean variation of individual trials from the means ranges from about 30% to about 60% of the means.

3. It appears in general from Table XVIII. that the greater means go with the greater variations, i. e., the device shows the more accurate person, both by the relatively greater mean inaccuracy and by the greater irregularity in successive trials.

4. Owing to the fact that the maximum time required by any subject for the trials made at one time was never over five minutes, and to the fact that the writing movement is so thoroughly habituated, fatigue was practically excluded.

5. W. B. made about 800 trials, extending over a period of three weeks, without showing an observable improvement from practice.

School Tests on Precision.

Writing Movement.

With a few exceptions, the same pupils tested in the rate experiments were tested for precision.

Apparatus: Strips of platinum foil were pasted smoothly on plate glass so as to make an angle of 2½ degrees. A small steel needle, set in a common wooden penholder, served as stylus. Three to four Le Clanche cells constituted the battery. A telegraph sounder gave the signal when the needle touched the platinum.

Course of the Experiments: The child was seated in front of the table where the glass plate lay. The latter was placed in such a position that the line along which the stylus was to be drawn should make an angle of 45°—50° with the frontal plane of the subject, when the right hand was used; and an angle of 130°—135°, when the left hand was to be used. The stylus was in each case placed between the arms of the instrument, 30mm. from the 0 point, and drawn toward the 0 point until contact was made. Six trials were made with each hand, three movements in each case being made away from the body, and three toward the body. The point of contact was recorded. The child learned what he was expected to do as follows: (A.) In nearly every case he looked on while one or more of his comrades went through the tests. (B.) He received plain directions, e. g., "Take the pen; hold it so; put the point here; draw the pen so, without touching either side," etc. (C.) He was made to try several times, until it was quite certain that he knew what he was expected to do. In some cases with very small and very stupid children, it proved impossible to make them understand what they were expected to do. Such cases, after long and patient trial, were abandoned. But records were not excluded because of being unusually inaccurate, if it could be ascertained from the child's answers and efforts that he knew what to try to do. The entire series of precision tests in the schools of Worcester was taken with scrupulous attention to every detail by my wife, Mrs. Lotta Lowe Bryan.

Classification of Results.

The results were classified according to the age and sex of the subjects, according to the hand used, and according to the direction of movement. Each class of results was treated by the method described, page 180. The Table XX. gives the results. The numbers before the colons give the numerical weights of the results after the colons; the latter give twice the distance in mm. within which 68% of deviations fall. Results with a weight of 150 or more are printed in heavy type.

Table XX.

School Tests on Precision.

Part of Scale		I 1—5	II 6—10	III 11—15	IV 16—20	V 21—25	VI 26—30
	Age	W't mm	W't mm	W't mm	W't mm	W't mm	W't mm
Boys Right Down	6		17 : .69	152 : .45	304 : .44	229 : .43	
	7		62 : .40	237 : .38	424 : .41	302 : .39	
	8	15 : .23	168 : .30	399 : .30	490 : .33		
	9	49 : .16	283 : .26	508 : .30	610 : .31		
	10	45 : .25	251 : .26	472 : .29	214 : .35		
	11	84 : .14	305 : .24	504 : .26	108 : .25		
	12	61 : .17	247 : .26	423 : .28	285 : .27		
	13	153 : .17	401 : .19	294 : .21	203 : .28		
	14	173 : .14	433 : .20	571 : .23	238 : .27		
	15	71 : .17	293 : .24	455 : .25	96 : .29		
	16	48 : .27	256 : .23	366 : .25	78 : .28		
Boys Right Up	6		25 : .54	155 : .44	326 : .43	154 : .38	
	7		72 : .45	263 : .38	448 : .40	203 : .36	
	8	10 : .26	163 : .33	370 : .34	196 : .32		
	9	39 : .16	246 : .29	524 : .31	374 : .28		
	10	22 : .23	208 : .31	466 : .31	214 : .29		
	11	45 : .27	288 : .27	504 : .27	108 : .30		
	12	70 : .17	302 : .24	366 : .26			
	13	80 : .16	333 : .25	392 : .24			
	14	118 : .16	421 : .22	571 : .22	120 : .25		
	15	120 : .19	398 : .20	191 : .22			
	16	97 : .19	323 : .22	231 : .21			
Boys Left Down	6			62 : .59	171 : .54	305 : .54	78 : .53
	7			52 : .50	218 : .57	411 : .52	297 : .52
	8		31 : .52	165 : .41	358 : .48	476 : .41	99 : .42
	9		59 : .36	215 : .45	484 : .45	609 : .41	
	10		73 : .42	248 : .38	462 : .42	320 : .38	
	11	4 : .66	83 : .35	253 : .36	463 : .44		
	12	9 : .20	114 : .33	320 : .37	462 : .34		
	13	33 : .32	200 : .24	360 : .39	381 : .35		
	14	13 : .20	184 : .30	418 : .33	556 : .34	239 : .34	
	15	47 : .19	263 : .25	412 : .27	282 : .31	96 : .34	
	16	31 : .30	194 : .24	310 : .24	228 : .33		
Boys Left Up	6		10 : .63	57 : .48	166 : .56	289 : .56	231 : .53
	7		43 : .36	128 : .40	283 : .49	427 : .48	299 : .51
	8		42 : .40	181 : .40	342 : .47	453 : .45	201 : .51
	9	8 : .26	104 : .32	287 : .37	498 : .45	615 : .41	129 : .44
	10	26 : .20	135 : .26	295 : .35	464 : .39	318 : .41	
	11	11 : .20	93 : .37	298 : .34	473 : .40	214 : .36	
	12	38 : .16	122 : .29	328 : .35	458 : .36	96 : .35	
	13	58 : .17	223 : .22	377 : .29	471 : .34	302 : .37	
	14	94 : .16	263 : .22	460 : .32	572 : .32	120 : .33	
	15	56 : .17	242 : .26	406 : .27	575 : .30		
	16	59 : .19	219 : .22	348 : .28	231 : .29		

Table XX.—*Continued.*

School Tests on Precision.

Part of Scale		I 1—5	II 6—10	III 11—15	IV 16—20	V 21—25	VI 26—30
	Age	W't mm	W't mm	W't mm	W't mm	W't mm	W't mm
Girls Right Down	6	3 : .48	56 : .29	212 : .43	387 : .40		
	7		41 : .53	224 : .42	399 : .40	274 : .39	
	8	21 : .24	182 : .23	352 : .32	359 : .33		
	9	24 : .21	171 : .27	394 : .32	506 : .31		
	10	35 : .22	243 : .24	449 : .31			
	11	89 : .18	344 : .24	487 : .27			
	12	74 : .16	235 : .22	422 : .30	500 : .30		
	13	53 : .21	265 : .26	463 : .26	102 : .28		
	14	92 : .13	304 : .22	355 : .24	378 : .30		
	15	56 : .21	294 : .22	330 : .27	366 : .30		
	16	15 : .31	142 : .26	188 : .28			
Girls Right Up	6		79 : .34	218 : .43	307 : .43	83 : .41	84 : .43
	7		82 : .36	265 : .39	427 : .37	185 : .35	
	8	17 : .31	169 : .29	363 : .29	361 : .32		
	9	26 : .30	191 : .27	411 : .34	313 : .32		
	10	38 : .27	294 : .34	476 : .25	203 : .28		
	11	48 : .24	306 : .27	506 : .25			
	12	55 : .25	283 : .25	453 : .27	303 : .27		
	13	80 : .18	341 : .23	390 : .24			
	14	86 : .20	354 : .22	460 : .22	96 : .29		
	15	75 : .22	321 : .23	264 : .23	93 : .29		
	16	69 : .15	213 : .22				
Girls Left Down	6		4 : .50	82 : .48	202 : .50	356 : .57	84 : .45
	7		8 : .35	122 : .45	287 : .49	434 : .48	93 : .42
	8		25 : .34	147 : .48	365 : .48	275 : .40	
	9		33 : .43	172 : .43	383 : .51	318 : .42	
	10		42 : .36	176 : .44	413 : .47	203 : .38	
	11		79 : .31	276 : .41	465 : .38	465 : .38	105 : .40
	12	3 : .21	72 : .34	253 : .40	440 : .43	203 : .34	
	13	9 : .74	146 : .30	351 : .35	482 : .34		
	14	7 : .57	169 : .31	348 : .31	447 : .32	191 : .41	
	15	28 : .22	176 : .24	323 : .32	427 : .34	184 : .39	
	16	6 : .48	122 : .27	212 : .32	150 : .33		
Girls Left Up	6		23 : .40	83 : .44	202 : .54	370 : .55	84 : .48
	7		7 : .49	86 : .40	265 : .53	343 : .47	
	8	9 : .34	62 : .27	208 : .42	348 : .42	447 : .44	
	9		56 : .40	208 : .39	401 : .42	505 : .45	108 : .41
	10	17 : .27	102 : .28	239 : .35	421 : .42	298 : .42	
	11	57 : .13	178 : .23	338 : .32	451 : .37	410 : .39	
	12	34 : .22	148 : .26	347 : .32	465 : .34	303 : .39	
	13	23 : .12	136 : .28	335 : .34	470 : .36	203 : .39	
	14	17 : .21	146 : .32	316 : .33	342 : .35	281 : .38	
	15	24 : .18	169 : .27	348 : .32	345 : .32	366 : .37	
	16	21 : .27	124 : .25	222 : .27	99 : .32	31 : .33	

Trustworthiness of Results.

1. Owing to the fact that the arithmetical mean of the individual results was not determined, it is not possible to give in the ordinary way the mean individual variation. In order to exhibit, however, the relative individual variation, I have determined for each of the 88 sets of results, the smallest distance along the scale within which two thirds of the individual results fall. In the following table these values, each divided by 2, are given as approximate measures of the individual distribution. It will be observed that the individual variation is greater for the left hand than for the right, and tends to decrease with advancing age.

TABLE XXI.

Table of values of smallest distance along the scale within which two thirds of hits fall, in mm.
2

	6	7	8	9	10	11	12	13	14	15	16
B. R. D.	4.	4.5	3.5	3.9	3.7	3.6	4.1	2.9	3.3	3.2	2.9
B. R. U.	4.5	4.	3.8	3.5	3.	3.1	3.2	3.	3.2	2.6	2.8
B. L. D.	5.4	4.5	4.2	4.3	4.3	4.4	3.8	4.9	4.	4.	4.1
B. L. U.	5.4	5.4	5.3	5.2	5.2	4.5	4.5	5.2	5.2	4.	3.9
G. R. D.	3.9	3.5	4.5	4.	3.8	3.5	4.6	3.5	3.6	3.6	3.
G. R. U.	4.	3.9	3.8	4.2	2.7	3.	3.6	3.	2.7	3.1	2.7
G. L. D.	4.6	4.8	3.5	3.8	3.9	4.	3.9	3.9	4.	5.2	3.4
G. L. U.	5.1	4.2	4.	4.2	5.5	6.3	5.	4.6	4.5	4.	3.5

2. A method of determining within certain limits the probable trustworthiness of results is afforded by a comparison of results from boys and from girls.

It appears that the maximum difference between a result for boys and the corresponding result for girls is .09 mm.; that the mean difference between boys and girls for the right hand is .004 mm., and for the left hand .007 mm.; and that 68.3% of the differences do not differ from the mean, for the right hand more than .02 mm., and for the left hand more than .029 mm.

This calculation is analogous to that for determining the mean variable error after the constant error has been found.

These numbers then, .02 mm. for the right hand and .03 mm. for the left hand, are measures of the probable mean variation of the results given in the table.

These numbers are unfortunately not so insignificant as may at first appear. The total reductions in the mean deviation between 6 and 16 are for the right hand about .23 mm. and for the left hand about .32 mm. This would show the average yearly reduction of the mean deviation to be for the right hand about .023 mm., and for the left hand about .032 mm. An examination of the table of actual yearly reductions of the mean deviations shows that the yearly plus or minus change in the mean deviation ranges from 0 to .098 mm. for the right hand, and from 0 to .085 mm. for the left hand. It appears, therefore, that in many cases the limit of doubt attaching to the results is greater than the change by growth in one year, and in some cases considerably more.

Although three times as many experiments were made upon an individual in each set of precision tests as in the rate tests, and although by the method of treatment each single trial by the pupil furnished information as to the precision at many points in its course, so that the numerical weights of the precision results are many times greater than the numerical weights of the rate results,—yet the former are still insufficient to define clearly the amounts of yearly growth. This result, which evidently comes from the much greater variability in the power to make precise movements than in the power to move at a maximum rate, is itself significant; but it limits greatly the possibility of deriving trustworthy conclusions concerning the development of precision of movement. In the following, only those conclusions will be given which stand apparently clear of doubt, in connection with all information possessed by the author for determining the several degrees of probability.

Variation in the Precision at Different Parts of the Scale.

It may be observed in almost every set of results that the mean precision increases as the apex of the angle is approached. This does not, of course, mean that fewer touches per hundred trials are made, but fewer, in proportion to the space between the arms of the instrument. It seems probable that this is due to the more perfect concentration of attention as the task becomes more difficult. In all comparisons made in the following treatment, as, for example, between right and left, or as between one age and another, the results obtained within the same 5 mm. of the scale are compared.

Extreme Limit of Variation.

The total reductions in the mean deviations between ages 6 and 16 are as follows: Boys, right, down, .26 mm.; boys,

right, up, .24 mm.; girls, right, down, .21 mm.; girls, right, up, .21 mm.; boys, left, down, .33 mm.; boys, left, up, .34 mm.; girls, left, down, .33 mm.; girls, left, up, .28 mm. In each case the results are given in terms of 2x, where x is the mean deviation in one direction from the straight line which bisects the angle *a*.

Yearly Variation.

To determine the yearly gain or loss in precision as measured by the mean deviations (Table XX., pp. 186, 187): Subtract each result with a weight of 150 or more from the result just above it in the table; e. g., in table, B. R. D., subtract each result for age seven from the result for age six which falls in the same group (.38 from .45, .41 from .44, and .39 from .43). Take the mean of these differences. Proceed in like manner with the results for ages 7 and 8, 8 and 9, etc. This calculation was made for all the results in Table XX. No conclusion is drawn from these results which is not justified by the several individual results.

The most obvious fact which appears is the great gain made between ages 6 and 8. This can be shown by placing side by side the gain in those years and the total gain from 6 to 16.

TABLE XXII.

	Boys. R. Down	R. Up	L. Down	L. Up	Girls. R. Down	R. Up	L. Down	L Up
Reduction of Mean Deviation between 6–8.	mm. .128	.096	.098	.096	.090	.125	.095	.115
Reduction of Mean Deviation between 6–16.	.26	.24	.33	.34	.21	.21	.33	.28

Turning to the records from 12 to 16, I am unable to draw any conclusion as to the effect of the physiological changes in that period upon the degree of precision, except that the effect is too small to appear clearly from the amount of data possessed.

R. VERSUS L.

In the case of 305 individuals (boys and girls of 6, 9, 12, 15 and 16), each individual record was examined with reference to the superiority of the right hand over the left. Upward movements with the right hand were com-

pared with upward movements with the left hand, and likewise downward with downward. The six right hand records for each individual were paired with the six left hand records by taking the numbers in the order in which they stand in the original records ; i. e., the pairing was determined by chance. The following table shows the result of this comparison :

TABLE XXIII.

Age	No. of Comparisons.	R. Superior +	Equal. 0	R. Inferior —	% +	No. of Persons in whom R. was Always Best.
6 Boys,	153	123	3	30	78.8	9
Girls,	168	130	4	34	77.4	7
9 Boys,	258	215	6	37	83 3	20
Girls,	216	168	9	39	77.7	5
12 Boys,	192	154	6	32	80.2	9
Girls,	204	167	4	33	81.3	8
15 Boys,	192	135	15	42	70.3	1
Girls,	186	126	18	42	67.7	7
16 Boys,	156	101	8	47	64.7	3
Girls,	102	72	6	24	70.6	3
Total,	1830	1391	79	360	76.	72 = (23 + %)
Persons,	305					

The table shows (A) that only in the case of 72 individuals out of 305 (23 %) does every right hand trial exceed in precision the left hand trial with which it is compared. (B) That in 1,391 out of 1,830 comparisons (76%) the right hand result is superior to the left. (C) That the per cent. of advantage by the right hand is less at 15 and 16 than at 6, 9, or 12 years of age.

A comparison of the mean values given in the right hand tables, pages 88 +, with those from the left hand tables shows in 78 cases out of 83 the right hand superior to the left.

The amount of superiority of right over left varies remarkably with age. If the values of (r–l) be determined by sub-

tracting each r value in the table, with a weight of 150 or more, from the corresponding l value, and if the mean of these (l-r) values be determined for each age, it appears that for both directions of movement, for boys and for girls, there is a decrease in the value of (l-r) with age. If the mean difference between r and l for each age be determined (including in the mean the results for both directions of movement, and for both sexes), we have:

Average Superiority of R. over L. in terms of x. mm.

Age,	6	7	8	9	10	11	12	13	14	15	16
Av. x,	.122,	.12,	.114,	.101,	.097,	.09,	.087,	.06,	.07,	.038,	.025

Boys and Girls.

An examination of results on page 188 shows that with either hand, the boys are very slightly superior to the girls in precision.

Mean superiority of boys' right hand,	.004 mm.
" " " " left "	.007 mm.

In 47 comparisons of right hand results the boys are superior 24 times; girls 13 times; boys and girls equal 10 times.

In 52 comparisons of left hand results boys are superior 27 times; girls superior 22 times; boys and girls equal 3 times.

In the 99 comparisons, boys were superior 51.5%; girls superior 35.3%; boys and girls equal 13.2%.

Precision Experiments.

Probing Movement.

Gowers (13) quotes Blix as proposing to determine the degree of incipient ataxia by requiring the patient to tap several times with a pencil, endeavoring each time to strike a fixed point on the paper. The distances of the points actually struck from the fixed point furnish material for estimating the degree of ataxia when compared with results from normal individuals.

The objection to this method on account of the great labor involved (Gowers I. 5), may be removed by using the following device: Paste smoothly upon a slab of plate glass a one □ cm. piece of platinum foil perforated by a circular hole 1 mm. in radius and connected with one pole of a small battery. To the other pole of the battery attach by a fine flexible wire a steel needle, set in a wooden pen-holder. Required to hold the point of the needle at a fixed distance perpendicularly above the centre of the hole, and at command to tap the glass

within the hole. A telegraph sounder gives the signal if contact is made. If the hole in the platinum be of such a size that a considerable per cent. of trials falls within, and another considerable per cent. falls without it, then the number of hits within, divided by the whole number of trials is the empirical probability of hitting within that area. The radius x of the hole being known, the value of h can be determined from the Probability Integral. If desired, an x can be determined corresponding to a probability .683, that is, one can determine from the ascertained probability, and the known value of x, the x which must be used in order that 68.3% of the trials shall be successful.

If an electric counter were used (such as that of Ewald or the apparatus of Dr. E. C. Sanford, already mentioned), and if one hundred trials were made, the reading on the clock face would be the empirical probability (p) in per cent. of failing to hit within the hole; (100-p) would then equal the probability of succeeding. If the size of the hole were kept constant, the values of t in the Table of the Probability Integral $\frac{2}{\sqrt{\pi}}\int_0^t \varepsilon^{-t^2}\, dt$ would always be equal to $k\,h$, the value of k varying with the unit in which the radius of the hole is expressed. It would be very easy to have the Probability Integral Table printed upon a convenient card-board for immediate reference in the clinic; so that if the average value and variation of h in normal cases were determined, it would be a matter of a few moments to obtain this test of incipient ataxia.

As a clinical test, however, this method is open to one serious danger. Probably for the reason that the movement is an unusual one, the subject makes very awkward movements at first; and owing to the fact that the movement is not difficult to learn, he makes very rapid improvement. This is shown in the following record made by myself. Each number in the table represents the number of failures to hit within the hole, ten trials being made in each case. In one set of trials the wrist moved and the other joints were kept still; in a second set of trials the elbow alone was moved; and in a third set the shoulder alone was moved. The conditions were kept as nearly possible the same in successive trials. It is evident in each case that the comparatively small amount of practice has greatly reduced the number of failures.

TABLE XXIV.

Table showing number of failures in ten trials; 60 sets of ten trials each. Distance moved 1 cm. Trial every 2 seconds.

	RIGHT.			LEFT.		
No. trials.	Shoulder.	Elbow.	Wrist.	Shoulder.	Elbow.	Wrist.
60	4	8	2	3	3	6
60	5	2	1	3	4	7
60	4	2	3	4	6	4
60	2	1	0	9	5	4
60	1	2	0	5	4	0
60	2	4	1	4	5	0
60	1	2	0	6	2	1
60	0	0	0	7	1	0
60	1	1	0	3	0	1
60	0	3	0	1	3	4
600	20	25	7	45	33	27

SCHOOL TESTS ON PRECISION.

Probing Movement.

With few exceptions the children tested by the foregoing methods were tested also for precision in the movement just described. Five trials were made with the right hand and five with the left. A board was held in position 6 mm. above the apparatus; the pen-holder was each time lifted until its upper end touched this board. It cannot be guaranteed that the pen will always be held in a perfect perpendicular, and accordingly the minimum distance to be moved, 6 mm., was sometimes slightly increased. If we assume what is quite certain, that in no case the pen was permitted to slant so much as thirty degrees, the maximum distance moved was always less than 8 mm.

The forearm was allowed to rest upon the table. The pen was directed mainly by the movement of the wrist, in a slight degree sometimes by movement of the elbow. Concrete directions by word and example, as in the writing move-

ment test, were given. No record was taken unless and until the child gave satisfactory evidence that the task required was understood. The results were classified according to the age and sex of the pupil and according to the hand used.

In the foregoing pages (192-193) the method of treating such results has been shown. It is only necessary here to say that in the manner described the probability of tapping within the hole without touching the platinum was determined for each set into which the results were classified. From this probability and the known value of x, the radius of the hole, were determined the values of h in each case, and the radii of circles within which in the several cases two thirds of the results would probably fall. Table XXV. gives these results and Chart V. shows graphically the same facts.

TABLE XXV.

Table showing in mm. the radii of circles within which 68.3% cases would fall.

AGE.		6	7	8	9	10	11	12	13	14	15	16
Boys,	Right	1.10	.97	.87	.80	.67	.65	.53	.58	.60	.42	.44
	Left	2.09	1.69	1.50	1.05	1.01	.90	.86	.87	.96	.79	.94
Girls,	Right	.91	1.01	.85	.86	.69	.69	.59	.61	.53	.49	.40
	Left	1.84	1.24	1.15	1.27	1.05	1.02	.83	.97	.74	.82	.77

EXTREME LIMITS OF VARIATIONS.

The amounts of decrease in the mean deviations between ages 6 and 16 are shown by the foregoing table to be: for boys' right .68 mm.; boys' left 1.30 mm.; girls' right .61 mm.; girls' left 1.10 mm.

These numbers are all larger than those in the corresponding table for the writing movement, page. That is, the mean deviations are very much larger and the decrease in the absolute size of the mean deviation between ages 6 and 16 is very much greater. The relatively great gain between ages 6 and 8 does not appear here so decisively as in the writing movement.

As in the writing movement, the left hand reduces the mean deviation much more than does the right hand.

Except at the age of six, where boys are inferior to girls, no decisive difference appears between the sexes.

Résumé of Results from Precision Experiments.

1. In normal individuals, the precision of voluntary movement is subject to much greater variation than is the maximum rate of movement. This test will probably distinguish pathological from normal deviations surely, only when the ataxia exists in a considerable degree, or when many tests are made. (P. 189.)

2. The absolute size of deviations from the movement attempted decreases much more rapidly in the two or three years following the age of six than later. This is particularly true in the case of the right hand. (P. 190.)

3. In right-handed persons, the right hand is superior to the left in precision, in about 80% of individual cases. Between ages 6 and 16, the deviations of left hand movements decrease by a greater absolute amount than do those of right hand movements. This is true for boys and for girls, in both directions of the familiar writing movement, and in the unfamiliar probing movement. (P. 191.)

4. The errors are, of course, greater with the unfamiliar probing movement under the conditions described than with the familiar writing movement. The decrease of the absolute size of the mean deviations is also greater. (P. 195.)

5. There is little mean difference in precision between boys and girls. These results indicate a slight superiority in favor of boys. (P. 192.)

Strength and Endurance.

Out of a large number of strength and endurance tests, only those will be reported at present which bear upon the question of bilateral development.([22])

Apparatus: The literature of dynamometry shows general dissatisfaction with the apparatus and methods which have been employed.[1]

It has been shown that varying mechanical factors, in the instrument, in the mode of gripping, or in the size and shape of the hand, co-operate with the quantity of force exerted to determine the record and therefore render the record doubtful. The following comparisons are made with the assumption that in the long run neither hand of the same individual would likely have any mechanical advantage over the other. A form of apparatus was devised essentially similar to that proposed by Hamilton([20]), (that is, a mercury dynamometer, the mercury balanced by water, pressure being applied to a rubber bulb and transmitted by water to the mercury). Two

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[1]For a partial Bibliography of Dynamometry see Reference Handbook of Medical Sciences, II. 544. Cf. also Vierordt([21]).

of these dynamometers were made and placed in the same frame about 40 cm. apart so that pressure could be applied to both bulbs at once, or to either at pleasure. In the following experiments, ample time was given to rest between trials, except that when the two hands were used successively, the succession was immediate. The order in which the hands were used was alternated in successive tests. The following table gives the number of times the preferred hand was superior in strength in the cases of seven (University) adults :

TABLE XXVI.

Subjects		J. A. B.	T. L. B.	G. S. H.	W. B.	F. B. D.	J. L.	E. C. S.	Total
No. of Trials		13	18	15	39	18	8	13	124
Preferred hand stronger	Hands used separately	5(6)	7(9)	0(2)	17(19)	7(9)	4(4)	6(7)	46
	Hands used together	5(7)	6(9)	11(13)	18(20)	5(9)	4(4)	5(6)	54
Total		10	13	11	35	12	8	11	100

The numbers in parentheses show the number of trials.
Number of cases, preferred hand stronger=100=80.6%.
" " " " " not as strong=18=14.5%.
" " " hands equal=6=5.%.

It is shown that the preferred hand exerts more strength than the other hand, whether the hands are used separately or together in about 80% of the cases. This is almost precisely the probability obtained from the school tests, that a right side joint will be faster in a given case than the corresponding left side joint. In this connection the claim of Féré(23), that strength and rate vary together, and the suggestion that rate depends in part upon the intensity of innervation, will be recalled. Compare (p. 191) the probability of (R > L) in precision. Cf. Binet(30).

The same experiments tabulated above were used also to determine whether more strength can be exerted by a hand working alone, or by the same hand when the other hand is working also. The results show that 5 of the 6 adult subjects were able to exert more strength with the hand working alone in most, but not in all cases.

In 60% of (112) cases, the hand working alone was stronger than when the other hand was working also.

In 27.5% of cases, the hand working alone was not so strong as when the other hand was working also.

In 12.5% of cases, the result was the same.

Table XXVII. shows the number of trials made by each subject, the mean height in cm., to which the column of mercury could be raised by each hand working alone, and by each hand working at the same time with the other.

Table XXVII.

Maximal Grip.

		Hands Separately		Hands Together	
		Right	Left	Right	Left
	No. of Trials	cm.	cm.	cm.	cm.
T. L. B.	(9)	115	112	108	106
E. C. S.	(8)	79	75	74	72
J. L.	(4)	80	66	76	61
F. B. D.	(9)	113	109	109	106
W. B.	(20)	99.6	96.6	99	95.6
J. A. B.	(8)	84.4	78	84.2	82

Note on Endurance Tests.

A few tests were made to determine the number of seconds an amount of force equal to about two thirds of the maximum force could be exerted. It came out very clearly that the right hand has greater endurance than the left; that the endurance of each hand is greater when working alone than when working at the same time with the other; and that the endurance of each hand is lessened if the other hand has been wearied by an endurance test. These results, however, were obtained only upon a single subject, and require verification.

Table XXVIII.

Subject W. B. Table Showing Results of Endurance Tests.

		Hands Working Separately		Both Hands	
	No. of Trials	Right Hand	Left Hand	Right	Left
First Set	8	36″	30″	26″	26″
Second Set	10	36.1″	30.5″		

Av. endurance	of	right	hand	when	left	was		wearied	32.6″
"	"	"	"	"	"	"	"	unwearied	33.7″
"	"	"	left	"	"	right	"	wearied	28.4″
"	"	"	"	"	"	"	"	unwearied	31.2″

Average superiority of right over left when right hand came before left: 10.″

Average superiority of right over left when right hand came after left: 1.2″

THEORETICAL.

In the foregoing pages I have given the immediate results of the experiments made, without theoretical comment or inference. Following are suggestions of probable conclusions from the facts:

I.

The maximum rate of voluntary rhythmically repeated movement is probably a critical test of voluntary control.

(a) While it does not appear that the rate of rhythmical "resulting movements" is identical with the rate of innervation, it can scarcely be doubted that the rate and intensity of innervation affect the rate of resulting movements. Von Kries says:

"Das wir in dem Rhythmus der Muskel Anschwellungen wirklich den Rhythmus der Inervation erhalten, das wird, wie ich glaube, kaum bezweifelt werden." This has been assumed by most studies of the rate of innervation. (24, p. 9. See also 25, p. 10.)

If this be true the decrease in the rate of the muscle rhythm (Griffiths, see p. 138) with fatigue is in all likelihood cause or part of the cause of the simultaneous decrease in the rate of the "resulting movements."

(b) The maximum rate of rhythmically repeated voluntary movement is probably a test of the power of voluntary arrest and reversal.

It was shown from experiments by Von Kries (p. 138), and confirmed (p. 150), that variations in the amplitude of movement within wide limits do not affect the rate. This paradoxical result,—which I have found to hold also for eye movements within the angle of usual movement,—is due to one or both of the following causes. For small distances, and especially for distances less than those usually passed over, the times of arrest, reversal, and of passing through the space nearest the points of reversal, may be slightly increased. In all cases the sum of these times must be so great in proportion to the time occupied in passing through the middle space that a slight increase of the latter is inappreciable.

That is to say, the rate of tapping is almost identical with the rate of voluntary arrest and reversal.

(c) The maximum rate of movement probably furnishes a test of the general condition of the central nervous system.

In this connection, Dresslar's(26) demonstration that mental excitement increases the rate, and that each day the rate probably varies with the tone of the central nervous system, is especially significant.

(d) The maximum rate of movement probably furnishes a test of the condition of the nerve centers by which the muscles involved in the movement are controlled.

If the conclusion of Mosso(27), Maggiora(28) and Lombard (29) be correct, that the working of a joint produces central fatigue, it is probable that the cases in which working a joint was followed by a lowering of its rate are to be explained in part, at least, as due to the effect of central fatigue. The fact that the rate of a joint is lowered by local fatigue while the rate of other joints remains unaffected, indicates no finer physiological differentiation in the central nervous system than the fact that we are able voluntarily to move one joint while the adjacent joints remain still. It would strongly confirm this view if it should appear that fatigue through one joint affects the rate of the corresponding joint on the other side.

II.

The History of the period from 12 to 16 in girls (see pages 161 and 174) and from 13 to 16 in boys, exhibiting in turn acceleration, decline and recovery of rate ability, presents what is, at any rate, a suggestive analogy to the course of ordinary over-tension, fatigue and recovery of the nerve centers. It would seem something more than a reasonable surmise that the general acceleration of the rate in girls from 12 to 13, and in boys from 13 to 14, is an expression of high tension in the nerve centers in many individuals at those ages; that the decline following is an expression of nervous fatigue consequent upon the functional changes at those periods; and that the re-acceleration is a sign of recovery from that fatigue. It is significant that (page 174) the antecedent acceleration and the decline are more extreme in girls than in boys, and that the girls recover more slowly. It seems not unlikely that these facts may prove of hygienic significance.[1]

[1] Note the result of Bowditch (8, 10 and 22, Reports State Board of Health of Mass.), of Peckham (6th Report State Board of Health of Wisconsin), and of others reported by them showing that boys exceed girls in weight and height at all ages from 5 to 18, except from about 12½ to 14½. Dr. Gerald M. West tells me that the measurements of Worcester school children by Dr. Franz Boas and himself show the same result. See also Prof. Bowditch's explanation by the theory of antagonism between growth and reproduction. (Op. cit. 8, 283.)

III.

The fact that the hand is at first inferior in rate ability to the arm (pp. 169-172) is perhaps explained, and its genetic significance is emphasized, by the observation made upon nearly, if not quite, every child of five and six, that the clasping tendency is still very strong. This is shown by the evident —́— - | —́— - | —́— - | rhythm of up and down strokes or by testing the force of downward pressure.

IV.—Résumé of Results Touching Bilaterality.

I. In the right-handed subjects, the right hand and arm are superior to the left in strength, rate and precision in a majority of trials. In few subjects is the right hand superior in every trial. The probability from these researches that in a single trial taken at random the right hand will exceed the left in strength, rate or precision is about 75% to 80%, the probability that the right hand will not be inferior to the left in such a trial is about 85% to 90%.

2. The effects of effort through either upper extremity are probably shared in some degree by both. (a) Between the ages 6 and 16 the right hand and arm very little, if at all, outgrow the left in rate ability. Since it is certain that the right side joints have vastly more use, either the growth of rate ability has not been determined by use, or the effects of use on the right side have been shared by the corresponding joints on the left side. The fact that Dresslar found no effect from practice is to be taken in connection with the fact that his records show very little effect from practice upon the right hand. The preliminary practice, while perfecting apparatus, had, he thought, trained his hand about to its maximum before records were taken.

(b) Between the ages 6 and 16 the mean deviation from the movement intended is reduced by a greater absolute amount by the left hand than by the right. We are not justified in assuming that reduction in the absolute size of the mean deviation by a certain amount means the same degree of gain in voluntary control, whatever the mean deviation from which the reduction is made. It is certainly easier to reduce a mean deviation x to $\frac{x}{2}$ than to reduce the latter to zero. It would be a rash conclusion that there is a gain in precision by the right hand between 6 and 8 equal to its gain between 8 and 16, because the reduction in the absolute size of the mean deviation in the first period is about equal to that in the second. The fact that between the ages 6 and 16 the

reduction in the absolute size of the mean deviation, in the case of the unfamiliar probing movement, is about six times as great as that made in the case of a movement constantly practiced, can certainly not mean that there is actually a greater gain where there is infinitely less use.

The fact that decrease in the size of the mean deviations from the movement intended is greater with the left hand than with the right, with the right when it is little developed, in the less practiced movement, and that as the deviations become less, their reduction becomes slower,—must rather be held to indicate that great absolute reductions are characteristic of relatively low development; and that slow and steady reductions are characteristic of comparative escape from physiological ataxia. It is, nevertheless, certain that the right hand does not outgrow the left; and the fact that, at 15 and 16 years of age, the probability of (R $>$ L) is less than at 12, 9 or 6 years of age, seems to indicate that the left has actually gained upon the right. At all events the fact that the left hand should make such relative improvement both in ability to carry out an unpracticed (probing) movement, and in ability to carry out a movement in which the right hand has had all the practice, tends to confirm the probability of bilateral effects of practice. It is, of course, not to be forgotten that the practice in this case is largely mental. (See Stumpf([31]), Cattell & Fullerton([32]), Camerer([33]), Fechner ([34]).

(c) The amount of force which can be exerted through one hand and the time during which it can be exerted depend upon whether at the same time or just preceding, force has been exerted through the other hand.

(d) The maximum rate of a joint is *possibly* affected by the exertion of the corresponding joint on the other side in the time just preceding.

4. Corresponding joints have generally the same periods of acceleration and retardation of growth. But there is nearly always a considerable bilateral asymmetry of development; and the asymmetry is generally the greater as the growth is more rapid. The fact that the boys' right arm grows faster in rate-ability than that of girls, and grows more asymmetrically as compared with the left, that the hands outgrow the arms and show more bilateral asymmetry, and that periods of rapid growth are generally periods of increasing bilateral asymmetry, show that bilateral asymmetry is not to be regarded as abnormal, but rather as in some degree an attendant and sign of growth.

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NOTE.—I heartily acknowledge my indebtedness to all the members of the Psychological Faculty of Clark University for advice and assistance in this and other work in the University. Above all I am under obligation to Pres. G. Stanley Hall for directing me to and in the following research.
Specific credits are given in the text.

EXPLANATION OF RATE CHART I.

1. Abscissa=time. Years noted at bottom of chart.
2. Ordinate=rate. Seconds indicated on margin.
   The base line is assumed to represent 4 taps per second.
   All points are then fixed with reference to that line.
3. The solid lines connect the mean-rate points of successive years.
4. The inside dotted lines represent the limits of mean variation of the means.
5. The outside dotted lines represent the limits of mean individual variation.
6. Boys' charts on the left of the middle line; girls' on the right.

EXPLANATION OF (R-L) CHART II.

1. Abscissa=time. Years noted at bottom.
2. Ordinate=values of (R-L). Base line: (R-L)=o. R-L=1 indicated on margin.

——————— = Finger.
. . . . = Wrist.
—o—o—o—o— = Elbow.
++++++++++++++++ = Shoulder.
Boys to the left; girls to the right of middle line.

EXPLANATION OF BILATERAL ASYMMETRY CHART III.

Abscissa=time. Years noted at bottom of chart.
Ordinate=values of $\sqrt{\mu_B^2+\mu_L^2}$=function of mean individual variations of R and of L, and of μ_B=mean variation of individual (r-l) values from this mean. Value of ordinate=1 tap per sec. indicated on margin.

——————— = Line connection values of $\sqrt{\mu_B^2+\mu_L^2}$.
. . . . = " " " " μ_B.
Base line = " whose ordinate is zero.
Boys to the left; girls to the right of middle line.

EXPLANATION OF PRECISION: PROBING MOVEMENT CHART IV.

1. Abscissa=time. Years noted at bottom of chart.
2. Ordinate=values of the radii of circles within which 68.3% trials would fall. Values of ordinates, 1 mm. and 2 mm. indicated on margin.

The upper lines represent the records for the left hand.
The lower lines " " " " " right hand.
Boys to the left; girls to the right of middle line.

CHART I. RATE.

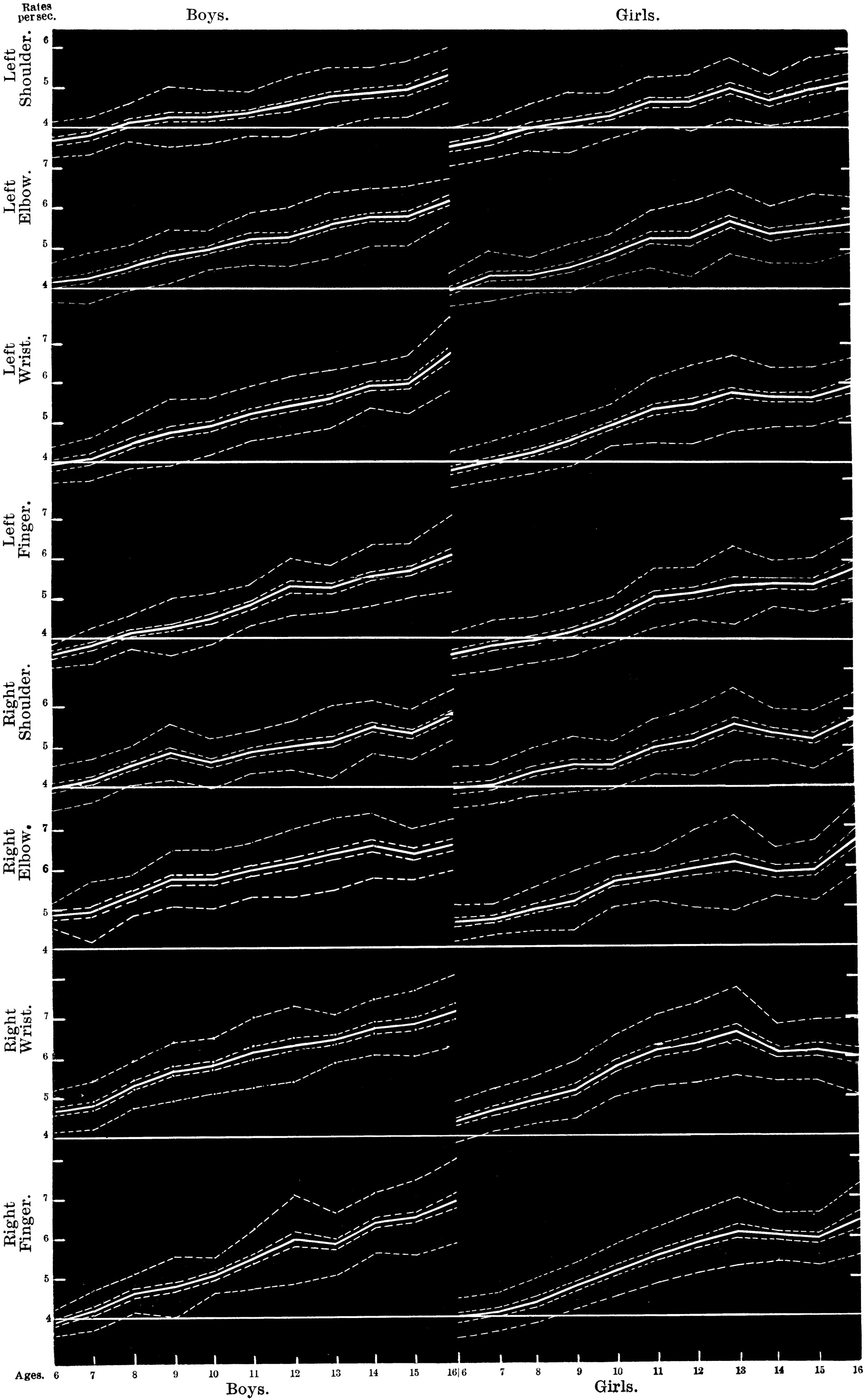
Rates per sec.
Boys.
Girls.
Left Shoulder.
Left Elbow.
Left Wrist.
Left Finger.
Right Shoulder.
Right Elbow.
Right Wrist.
Right Finger.
Ages. 6 7 8 9 10 11 12 13 14 15 16|6 7 8 9 10 11 12 13 14 15 16
Boys.
Girls.

CHART II. RATE: (R.-L.).

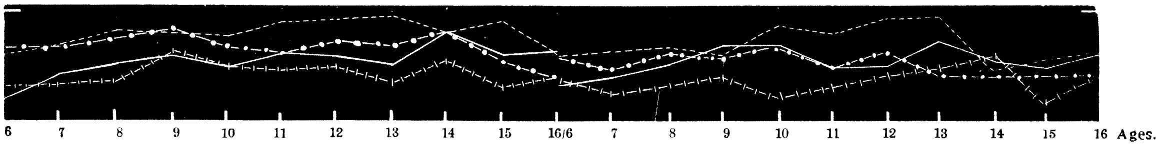

CHART IV. PRECISION: PROBING MOVEMENT.

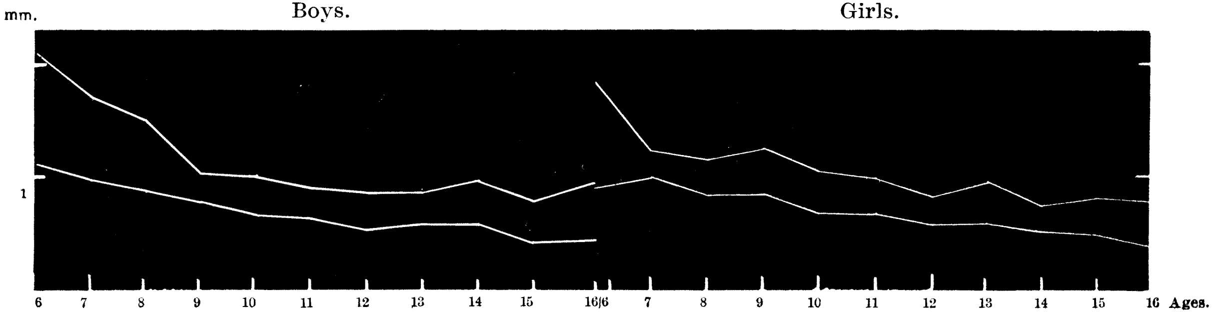

Chart III. Rate: Bilateral Asymmetry.